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NOTES ON THE DESIGN AND OPERATION OF SATELLITE TRACKING STATIONS FOR GEODETIC PURPOSES

by

The Staff of the
Smithsonian Institution
Astrophysical Observatory

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Introduction

Worldwide networks of photographic tracking stations have been observing artificial earth satellites since 1957, but until recently there has been little incentive for anyone to observe satellites independently. Now with the advent of flashing-light geodetic satellites, a modestly equipped observatory can locate itself, relative to other points on the earth, at least ten times more accurately than was ever possible before, to about 10 meters eventually. The desirability of independent observations is obvious, although such an undertaking should be done cooperatively with other stations.

These notes are intended as a preliminary aid to the design and operation of three types of optical geodetic stations (see table 1). Possible stations of comparable precision are classed in order of increasing complexity and cost:

Class C2: Camera fixed while operating; shutter and timing accurate to 0.05 second of time as required to determine background star positions; can be used for flashing-light satellites only.

Class C1: Camera on equatorial mounting to follow stars at the sidereal rate; shutter and timing accurate to 1 or 2 seconds of time; can be used for flashing-light satellites only.

Class B2: Camera fixed while operating; shutter and timing accurate to 0.001 second of time; can also be used for bright-passive as well as flashing-light satellites.

[1]This work was supported by grant NsG 87-60 from the National Aeronautics and Space Administration.

Table 1.--Classes of tracking station*

Class	Timing	Tracking	Uses
A	.001 sec	Variable speed	Bright-passive; flashing; faint;
B1	.001	Sidereal	Bright-passive; flashing
B2	.001	Fixed	Bright-passive; flashing
C1	1.0	Sidereal	Flashing
C2	.05	Fixed	Flashing

* Optics for all classes: at least 10-cm aperture; at least 40-cm focal length; at least $5^\circ \times 10^\circ$ field; preferably a focal length of 1 meter, an aperture exceeding 15 cm, and a field exceeding $5^\circ \times 10^\circ$.

Class B1: Camera on equatorial mounting to follow stars at the sidereal rate; shutter and timing accurate to 0.001 second of time; can also be used for bright-passive as well as flashing-light satellites.

Class A: More complex system in which camera can follow satellite motion; shutter and timing accurate to 0.001 second of time; can be used for all satellites, including faint-passive.

A Class A station will obviously cost more than the others; it will also be a powerful tool for serious astronomical uses, although no attempt will be made here to describe them. From a geodetic standpoint, all three types of station will achieve results of the same accuracy. Since these notes are based partly on experience, there are frequent references to the 12-station network of Baker-Nunn cameras operated by the Smithsonian Astrophysical Observatory with the active cooperation of nine countries. Originally established for the International Geophysical Year, this network is now supported by the U.S. National Aeronautics and Space Administration for the benefit of international scientific research. A somewhat comparable network of optical stations is operated by the USSR.

Camera (general comments)

Many instruments have been pressed into service to photograph satellites. Some have been newspaper cameras, others aerial photographic cameras; some ordinary astronomical cameras such as theodolites, still others specially designed cameras such as the Baker-Nunn. The optics of this last camera were designed by Dr. James G. Baker, and the mechanical system by Mr. Joseph Nunn. The optics were constructed by the Perkin-Elmer Corporation, and the mechanical parts by the Boller and Chivens Co.

For geodetic purposes, a satisfactory camera will have a focal length of at least 40 cm, but preferably about 1 meter, for adequate plate scale to give the final measuring precision of 1 second of arc required for geodetic purposes. The random effects of atmospheric refraction introduce position errors often exceeding 2 seconds of arc and set a sensible upper limit of focal length to less than 2 meters. The camera should also have a relatively large linear aperture, certainly 10 cm minimum and preferably 15 cm or more.

The camera should have a field of view at least $5^{\circ} \times 10^{\circ}$, the 5° being in the cross-track direction, to provide enough stars for convenient reduction and to allow for some error in pointing and starting the camera.

Mount and tracking mechanisms can range from the very simple to the very complex. The simplest is a stationary camera. Complexities can be added with an alt-azimuth or equatorial mounting with sidereal or tracking drives on one or more axes. Tracking can be at constant velocity over the photographed path or can provide for acceleration (see section on Camera mounts) during photography.

Probably the ultimate design would be a programmed drive with varying velocity on two or three axes of an alt-azimuth mount or a polar mount in which the polar axis can be sighted to any point in the sky, and the polar axis driven at varying speed. Such cameras would allow the tracking of a satellite over a greater portion of its arc without undue cross-track motion.

As an alternative to tracking, the camera plate or the optical path can be moved at a constant or a varying velocity. The problems associated with moving the plate with shutter and time-presentation equipment probably make plate-moving cameras a poor choice unless the cameras are exceptionally well engineered and constructed. Varying velocity rather than constant velocity during one satellite pass is desirable for more sophisticated systems, especially when the entire pass is to be photographed.

The lack of light-grasp of a small-aperture optical system may be partially compensated in sophisticated tracking devices that allow the satellite image to build up a sufficiently long exposure. The only requirement in this case is the photography of sufficient reference stars to ensure proper measurement.

The elimination of vibration is important. Mount vibration should be less than 1 second of arc. If possible, the camera should be remotely operated.

Camera optics

The class of a station is dictated more by considerations of mount, timing, and shutter construction than by the camera optics, since the optics of the camera must meet the minimum requirements stated below.

On a limited budget the optics used in a geodetic camera may be determined by the availability of surplus instruments or limited to optics that are employed in existing cameras.

The following formulas given in Sidgwick (1961, pp. 352 ff.) give a means of estimating the limiting magnitude for tracking a star under a particular set of conditions.

Limiting magnitude is given by

$$5 \log_{10} A + 2.15 \log_{10} t + 4 , \qquad (1)$$

for sidereal tracking with ultrarapid plates, and the optimum time of exposure T is

$$\log T = 1.5 + 2.325 \log \frac{F}{A} , \qquad (2)$$

where A is the aperture in cm, t is the exposure in minutes, and F is the focal ratio.

This gives limiting magnitudes for an f/3 camera of

17.0th magnitude for D = 25 cm;

16.4th magnitude for D = 20 cm;

15.9th magnitude for D = 13 cm.

The required exposures to give these limiting magnitudes are much longer than those normally used in tracking satellites so that these limiting magnitudes are grossly optimistic. Also, filtering in the optical system is not taken into account. The K-50 camera (90-cm focal length, f/4), for example, has in its optical train an orange filter (cutting off at 5100 Angstroms) that reduces transmission nearly one half. Tests of the K-50 camera using Tri-X film have produced

8th magnitude in 30 seconds;

9th magnitude in 45 seconds;

10 to 10.5th magnitude in 2 minutes.

The Baker-Nunn camera (50-cm focal length, effective f/1.25) with Royal-X Pan film gives a limiting magnitude of 14.5 at 20-second exposure, and 11.6 at 3.2-second. Normal exposures are between 3.2 and 0.2 seconds and yield for measurement stars that appear in the most precise catalogs.

The optical speed of the trailed image is directly proportional to the aperture squared and inversely proportional to the focal length and the image diameter.

The limiting magnitude for trailed images in any system can be found from

$$\frac{\omega}{L} = \frac{3.438}{E} k \frac{A^2}{fd} , \qquad (3)$$

where ω is the angular velocity in minutes of arc/second, L is the illumination in meter candles cast by the satellite on the surface of the earth, E is the exposure in meter candle seconds needed to produce an image on a given plate, k is the transmission coefficient of the system, A is the aperture, f is the focal length, and d is the diameter of the image spot; A, f and d are in millimeters (Henize, 1957).

Flashing-light satellites give effectively an instantaneous point-source exposure so that limiting camera sensitivity depends only on the operative image quality and diameter, efficiency of light passage through the system and photographic sensitivity as function of wavelength. Thus the sensitivity requirement for the camera takes the form that the quantity $A^2 K/(Ed)$ must exceed some constant that depends upon the integrated intensity and distance of the flashing light. Note that the reciprocity characteristics of the plates used will affect the results for different types of satellite observation.

Camera mounts

Depending upon the level of sophistication attempted, various methods of satellite photography may be useful for geodetic purposes. Before a mount -- whether fixed or tracking -- is chosen, the various possibilities should be considered (Veis, 1960).

Class C2 cameras, which are held in a fixed position, can be used to photograph flashing geodetic satellites. By this method the stars produce trails and the flashes appear as point images.

A Class C1 camera is mounted equatorially to follow the stars; the flashing geodetic satellite (invisible otherwise) produces flashes at known times (figure 1a). The photographic format then contains point images of the stars as well as point images of the flashes (Väisälä, 1946). A sophisticated development of the Class C1 camera into a B1 camera allows its use for non-flashing geodetic satellites. By means of a precise chopping shutter and a timing system accurate to .001 second the trail of the satellite is interrupted, and the timing of the interruptions recoreded (figure 1b).

If the camera is kept fixed so that both the stars and the object produce trails as images, a chopper must be used to interrupt the trails (figure 1c). Such a method is employed in the various types of ballistic cameras, which we call Class B2. It is obvious that these stations can photograph geodetic flashing satellites, although a sun-lit satellite must be especially bright to provide a trail.

A higher stage of sensitivity in satellite photography for geodetic purposes is achieved when the camera is provided with a tracking mechanism so that it can follow the satellite and thus obtain point images of extremely faint sun-lit satellites. Both the Baker-Nunn camera and the Smithsonian geodetic camera are equipped with such mechanisms. Tracking is provided on the former by driving the camera (figure 1d), whereas the geodetic camera keeps the lens assembly fixed and moves a photographic plate across the focal plane (figure 1e). In both cameras, special shutters chop the images, timed to a precision of .001 second (see section on Choppers).

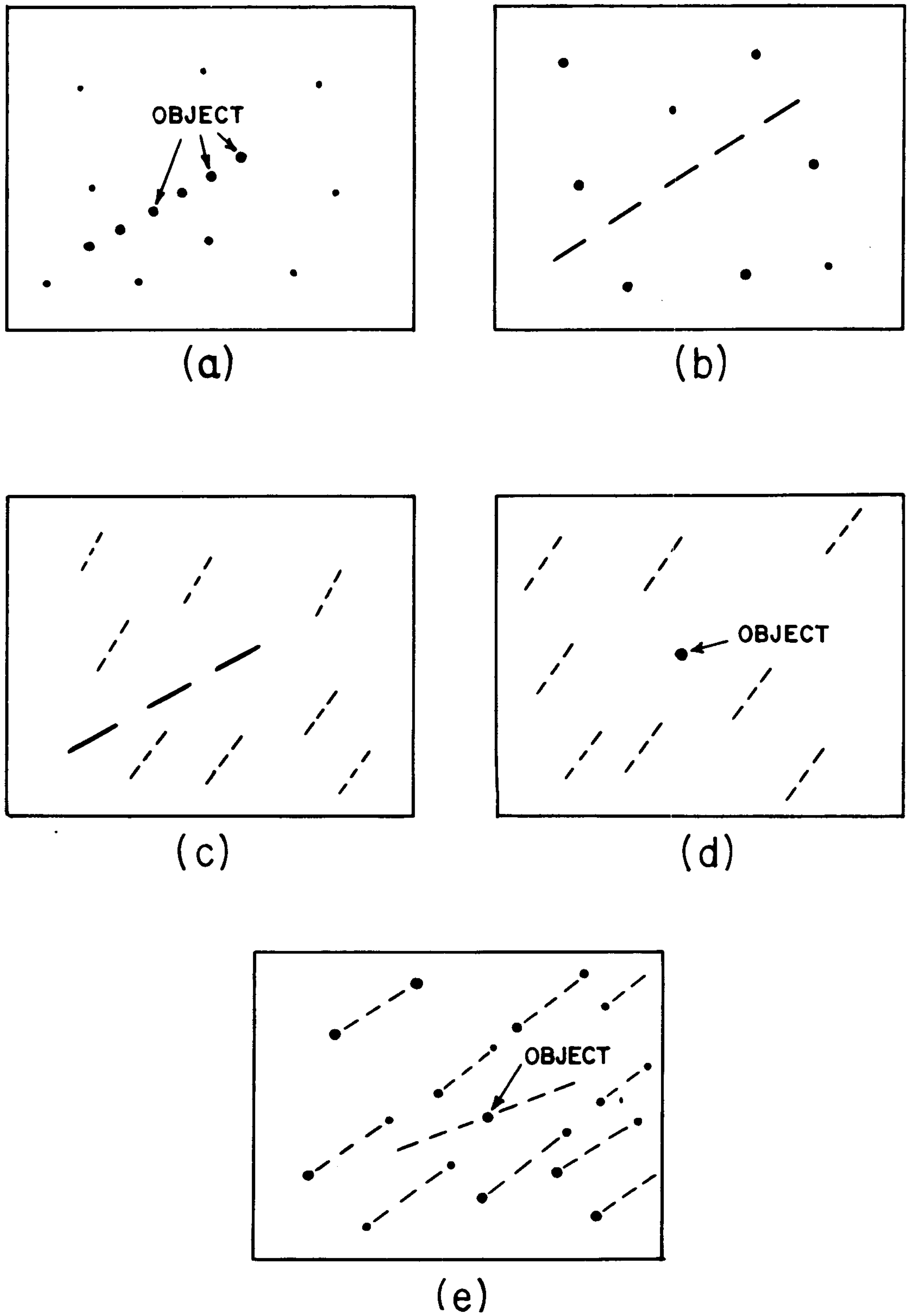

Figure 1.--Schematic version of satellites photographed with five methods.

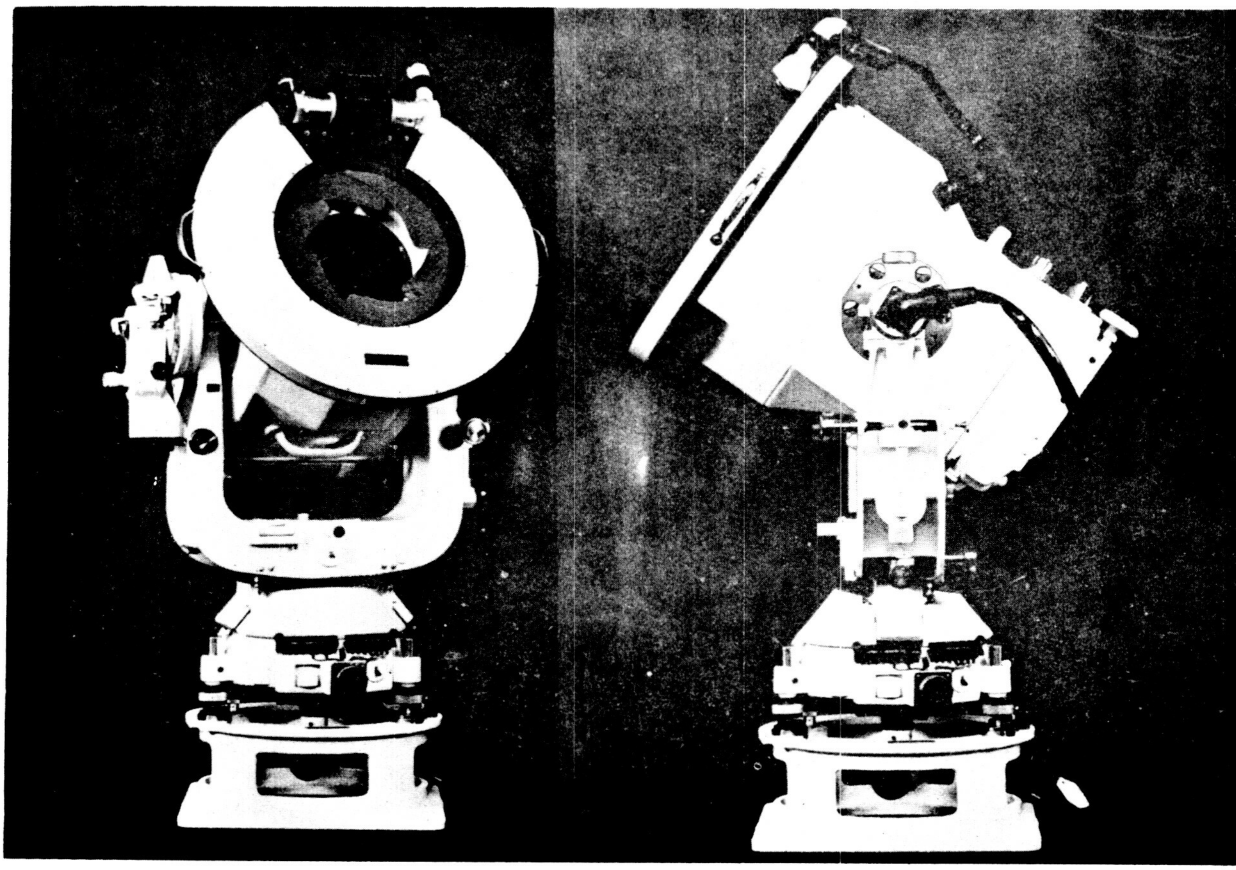

Figure 2.--A ballistic camera is shown in a sophisticated altitude-azimuth yoke mounting.

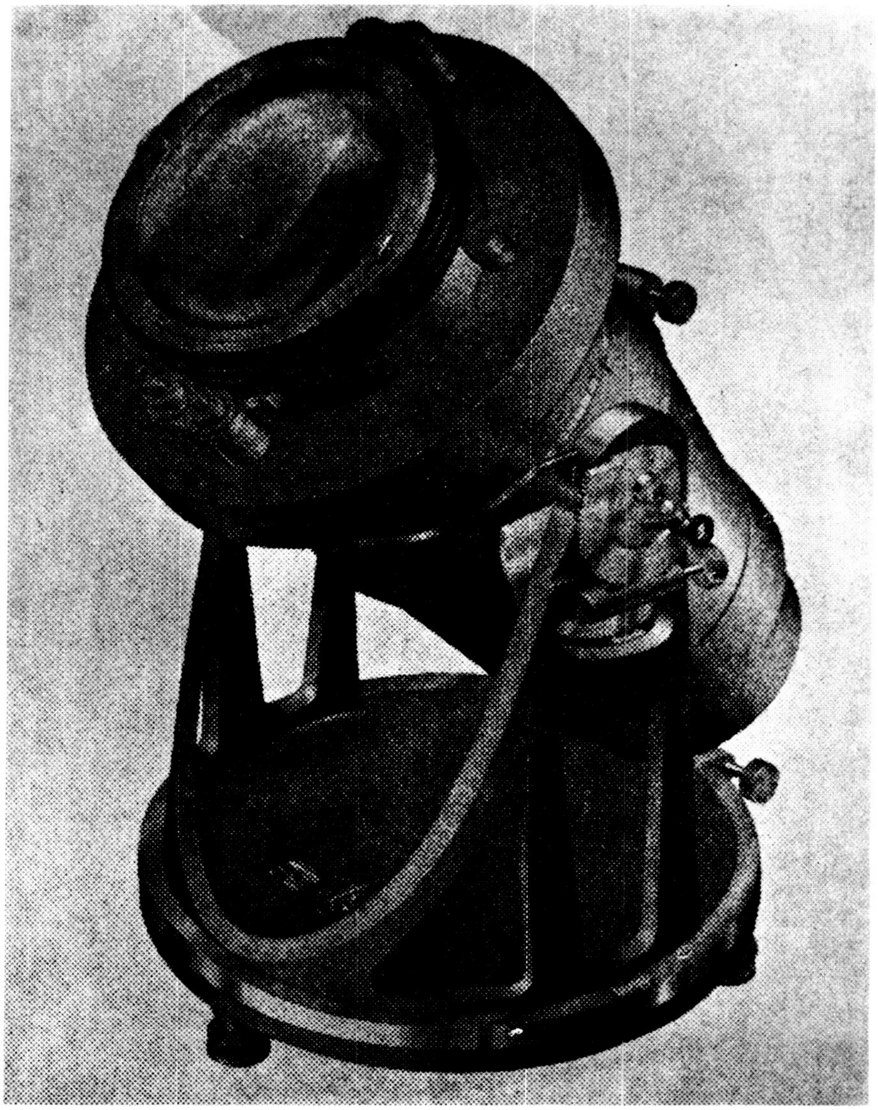

Figure 3.--One-inch steel plate is used to form the altitude-azimuth mounting for a 60-millimeter ballistic camera.

Mounting requirements

Of prime importance is the achievement of a mount virtually free of vibration. This can be accomplished by providing solid mounting piers, adequate wind protection, separation of the floors of the building or access platforms from the mount base, remote control of camera when possible, and controlled balance of the camera in all positions to prevent overhanging centers of balance and strains on the various axes. The camera must have full access to all parts of the sky, especially the pole and the zenith, in order to attain its full usefulness. Correct counterbalancing aids the operator in changing camera positions smoothly. Secondary considerations of compactness, simplicity of design, and low cost should also be kept in mind.

Altitude-azimuth mounts

Because cameras of Class B2 and Class C2 are held in a fixed position during an exposure, they lend themselves to a simplified mounting. For these cameras, an altitude-azimuth design can be used to provide movement in two planes, the horizontal or azimuth plane, and the vertical plane on which the altitude is set. Setting circles are required to an accuracy of only about 0.5 degree.

The altitude-azimuth mount of the yoke type (figure 2) is the best simple design for mounting a camera for geodetic work. It can readily be formed from plate steel (figure 3) or cast (Mason, 1957). The altitude shaft is supported at each end in trunnions mounted at the top of the uprights of the yoke. The design should provide sufficient depth of the uprights to allow the camera to swing through 90° of altitude. Locating the center of gravity of the camera at the point of intersection of the altitude and the azimuth axes provides smooth movement in altitude and simplifies the locking device for setting a position in that plane. At the base of the yoke, the azimuth axis, which is perpendicular to the horizon, can rotate in a bearing secured to the mount base. For proper alignment, a three-point suspension is necessary in the horizontal plane. The altitude-azimuth yoke mount has all the features of simplicity, compactness, and ease of operation. Cameras of approximately $5^{\circ} \times 10^{\circ}$ field with setting circles good to a 0.5° can easily be fixed on the satellite's predicted position.

The procedure for aligning the modified altitude-azimuth mounting of the Baker-Nunn camera is found in Rolff (1961).

Equatorial mounts

Although the altitude-azimuth mount is well suited for fixed camera photography, an equatorial mount can also be used to simplify plate reduction. The equatorial mount on a Bl camera and on the Smithsonian's geodetic camera has its polar axis parallel to the earth's axis of rotation, and its declination axis at right angles to it. Through use of a sidereal drive, the mount follows apparent motion of the stars and produces point images of the m.

Of the various types of equatorial mounts available, three suitable for a geodetic camera are discussed here:

The altitude-azimuth fork mounting can be converted to an equatorial by tilting the azimuth axis so that its altitude is equal to the latitude of the station; the azimuth axis thus becomes a polar axis (figure 4). This modification, which has been made on some Baker-Nunn cameras (figure 5), is useful for high-latitude stations. At lower latitudes, increased strain on the polar axis is present due to the increasing cantilever effect. The advantages of the altitude-azimuth fork mounting are that it has full access to the sky and that it does not need a declination counterpoise.

Another common equatorial is the German mounting, widely used in astronomical work (figure 6). It provides full-sky visibility and compactness of design with its single supporting pier on which the equatorial head is located. However, the weight of the camera must be counterbalanced at the end of the declination axis, thus adding to the weight of the system.

The modified English or cross-axis (figure 7) is another type of astronomical mounting that has long been used. The two-point suspension of the polar axis gives better support to the load. The offset of the camera from the polar axis allows for full-sky visibility. As with the German mounting, however, a counterweight is needed at the end of the declination axis.

The procedure for aligning an equatorial mounting can be found in many references (Sidgwick, 1961, for example).

There are many commercially available sidereal drives on the market; however, design literature can be found in Sidgwick (1961) and Ingalls (1957). In Miles (1963) a sidereal drive is discussed as well as an oscillator-amplifier circuit to provide a controlled frequency to the synchronous drive motor.

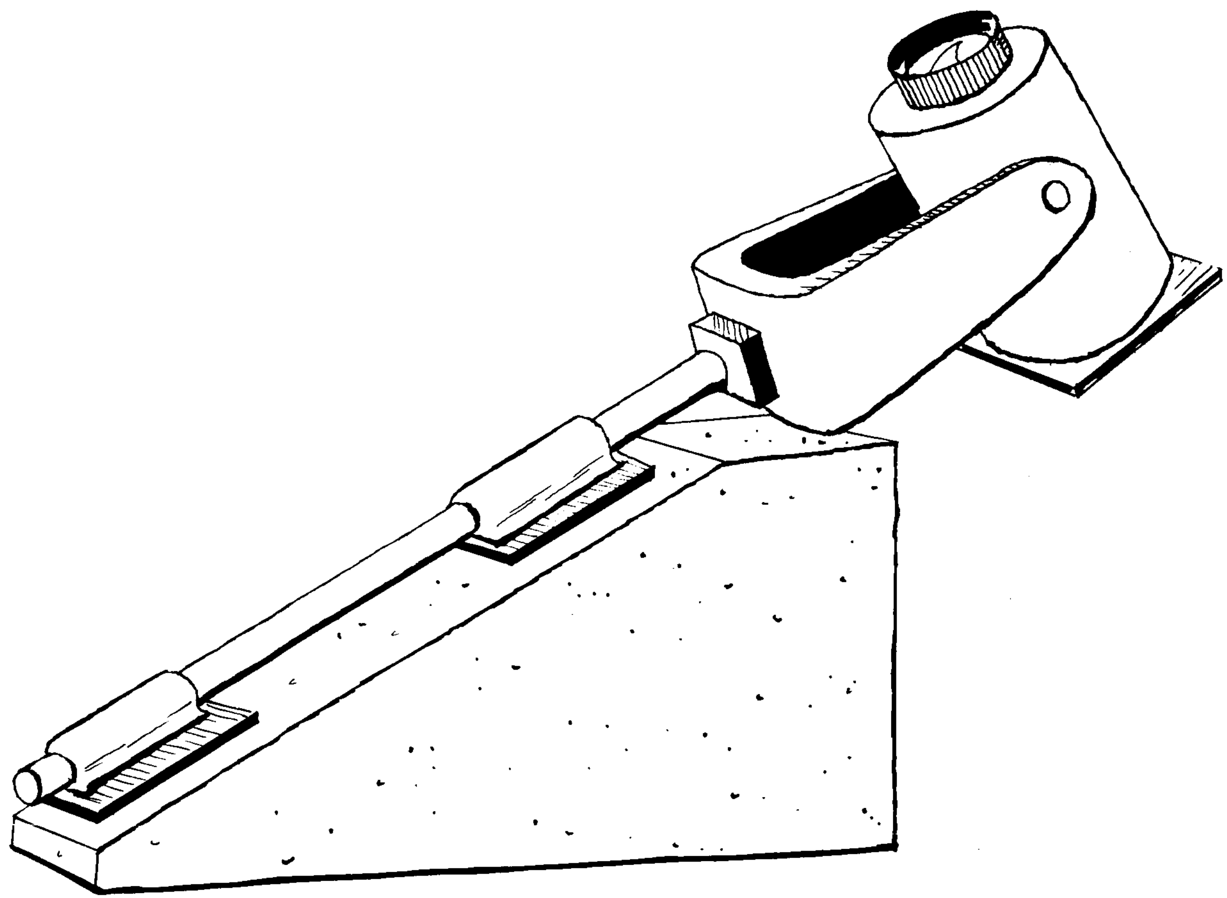

Figure 4.--Altitude-azimuth fork mounting modified into an equatorial.

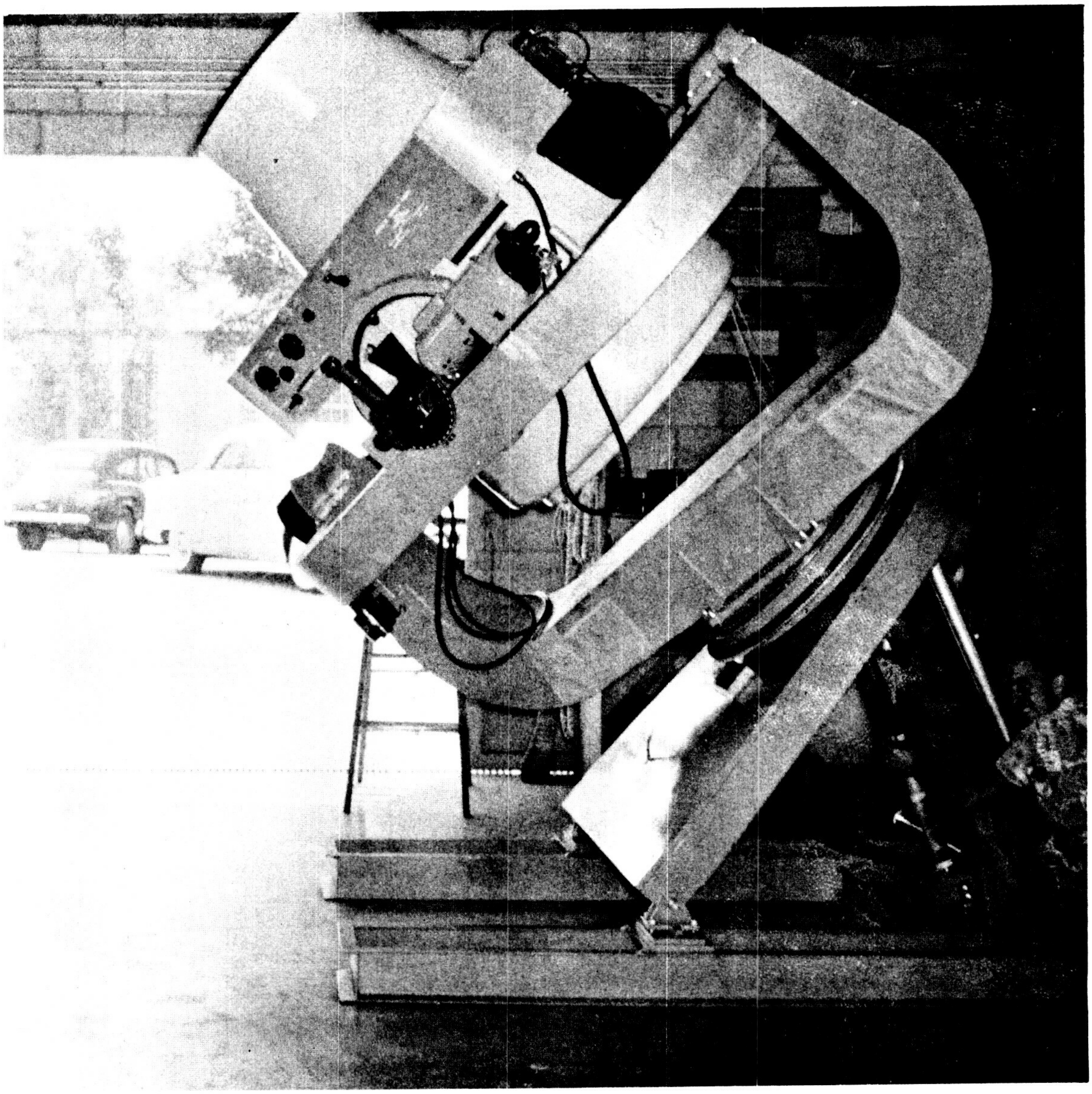

Figure 5.--The photograph shows a modified Baker-Nunn camera with its azimuth axis parallel to the axis of the earth's rotation.

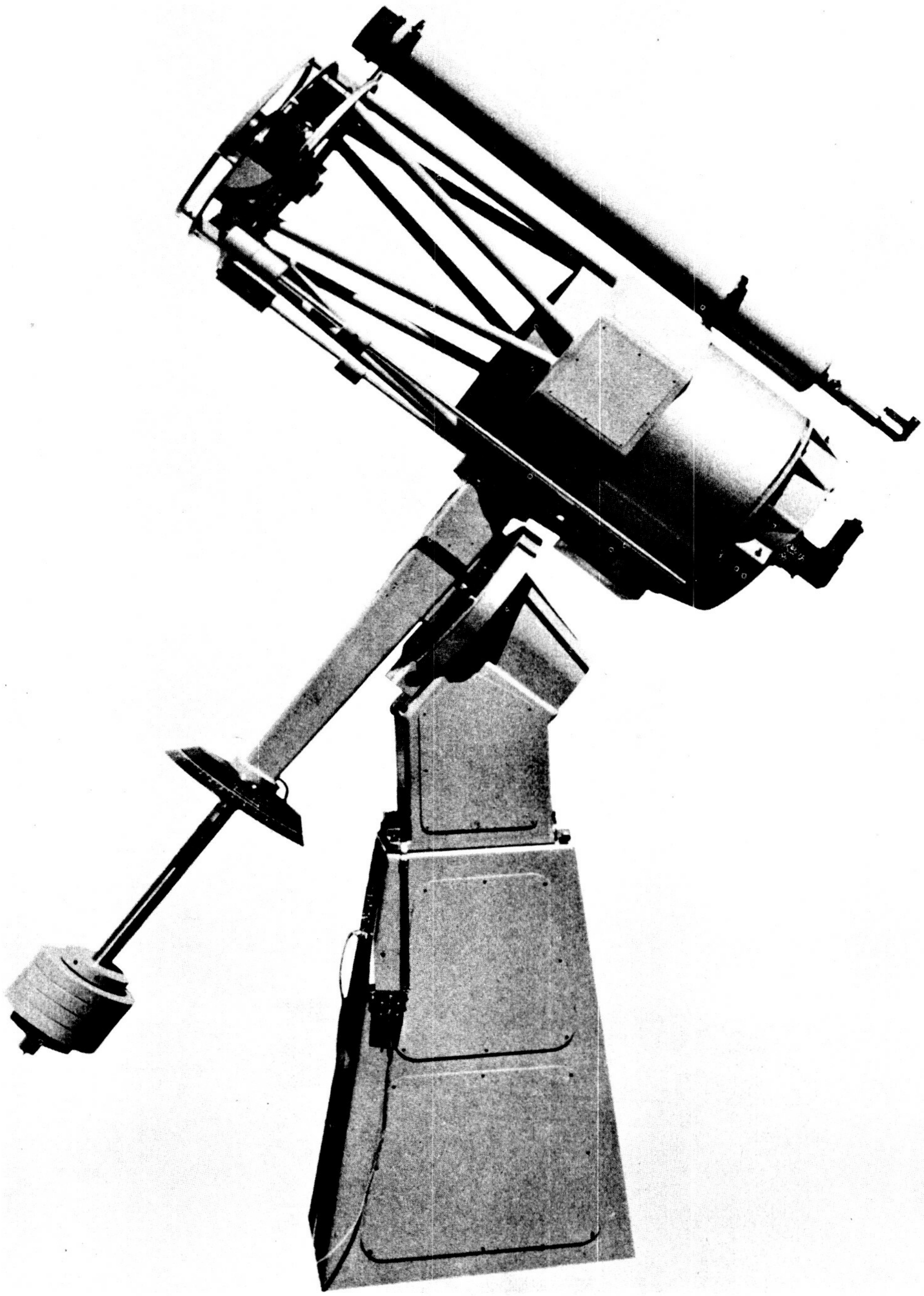

Figure 6.--The German equatorial mounting providing full sky visibility, has been used in astronomical work for many years.

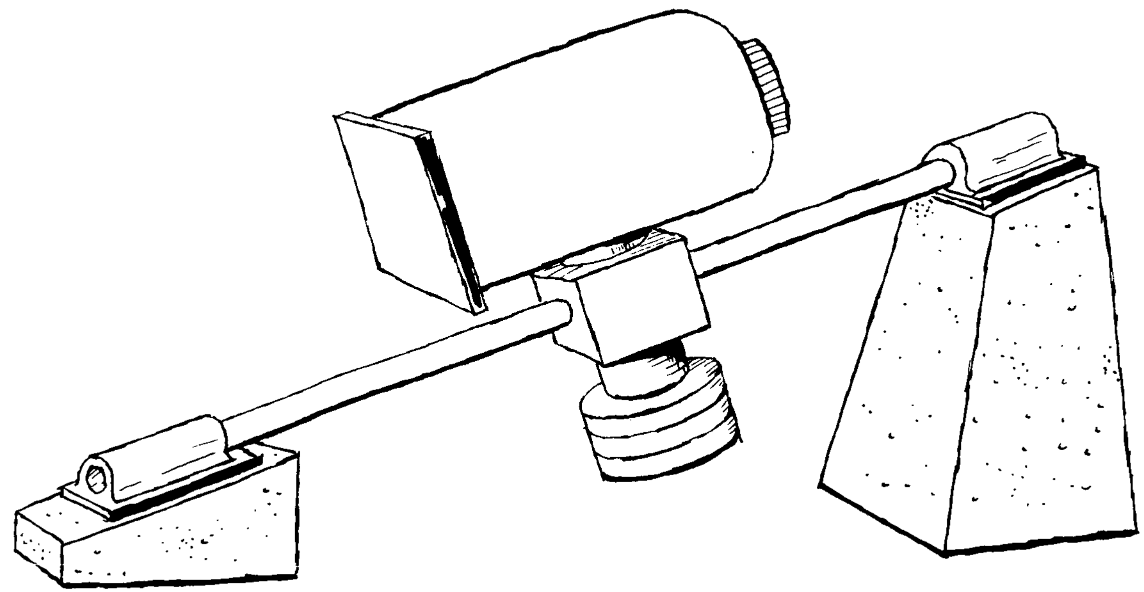

Figure 7.--The Modified English mounting allows two-point suspension of the load.

Tracking mounts

In order for a satellite to be photographed as a point image, the camera can be made to follow the path of the satellite as it moves across the sky, or the film or plate can be driven across the focal plane to compensate for the satellite's motion. The Smithsonian Astrophysical Observatory is using both of these methods in its satellite tracking cameras. The optical images can also be moved independently of the objective or camera for short intervals of time to follow satellite motions. Such highly specialized systems require special design and construction.

The motion of a satellite through the sky, as seen by a particular observer is usually very rapid. It deviates appreciably from a great circle and is rarely symmetrical in angular velocity with respect to its culmination point. Consequently, the path and the angular velocity of the satellite as observed from a point on the surface of the earth may change greatly between horizon and culmination. For these reasons, the traditional telescope mount designed to track stars is inadequate for tracking near-earth satellites. On the other hand, a mount preprogrammed to follow every possible path of the satellite, including changes in angular velocity, would be extremely complex. An effective compromise can be achieved by designing a tri-axis mount so that the third axis allows orientation of the camera to track along an arbitrary great circle. In this way approximations to the satellite's path are possible.

The Baker-Nunn camera (figure 8) sits in a gimbals ring fitted into the yoke of an altitude-azimuth mount. A Graham variable-speed drive is linked to the camera through a worm and worm-wheel. The camera can be driven across the sky at variable speeds from 0 to 7000 seconds of arc per second. In operation the camera's motion tracks the satellite with an accuracy of 1 percent.

The geodetic camera of the Smithsonian Astrophysical Observatory uses the other tracking method. The camera, which is held fixed on an equatorial mount, defines its tracking plane by the focal plane of the camera. The tracking direction is preset by a rotation of the back of the camera, thereby approximating the path of the satellite through the field of the camera. A 10 x 13 cm photographic plate is then driven across the focal plane of the camera at a rate calculated to compensate for the image motion.

Cameras with tracking capabilities are able to photograph both flashing and nonflashing, bright and faint, satellites, and lend themselves equally well to geodetic work or to maintaining orbits of faint satellites for other purposes.

Camera shutters

In order to begin and terminate an exposure, the camera must have a shutter mechanism. Special shutters or choppers are also used to produce coded breaks in the trailing image of either the satellite or the star. Shutter complexity can vary from the simple gross capping shutter to the louvered shutter on the BC-4 ballistic camera (figure 9). The required precision in time is 0.05 second for timing star trails, and 0.001 second for satellite motions.

Necessary general characteristics of a shutter are high-speed actuation, long life, and accurate repetition of the exposure cycle for those cameras taking multiple exposures during a satellite pass. A desirable characteristic is simplicity of construction, especially when the camera is to be used in the field. Shutters are categorized by position in the camera (for example: objective, intra-lens, or focal plane) and/or function or design (for example: louvered, iris, or capping).

Intra-lens shutter

Shutters of the intra-lens type are designed to be used between the front and the rear elements of a camera lens. The intra-lens shutter operates on the principle that all light entering the camera lens passes through the small area located between the elements of the lens. Because of their small dimensions in wide-angle systems, shutter-leaves operating near this region can have short time constants and thus sometimes be used as chopping shutters as well as capping shutters.

Intra-lens shutters may be subclassified into the drawer type (figure 10), in which the thin iris shutter leaves and connecting linkage are inserted between the two lens cells; or the circular type, in which the blades and activating mechanism are located in a circular-shaped casting to which the two individual lens cells are fastened.

The usual intra-lens shutter of either type has four or five blades that can be operated in various ways depending upon the design. The first method allows one set of leaves to operate in two directions per exposure, as in the Rapidyne shutter (figure 11). The second design has two sets of shutter leaves that move in one direction per exposure. A third design has only one set of shutter leaves, which move in one direction per exposure, as in the high-speed unidirectional intra-lens shutter (figure 12).

For an intra-lens shutter, the design of the lens determines the size of the circular aperture that must be covered by the shutter leaves; therefore, the highest shutter speed depends upon the size of the aperture of the lens. In many cases this produces a limit on the usefulness of intra-lens shutters for cameras of large aperture.

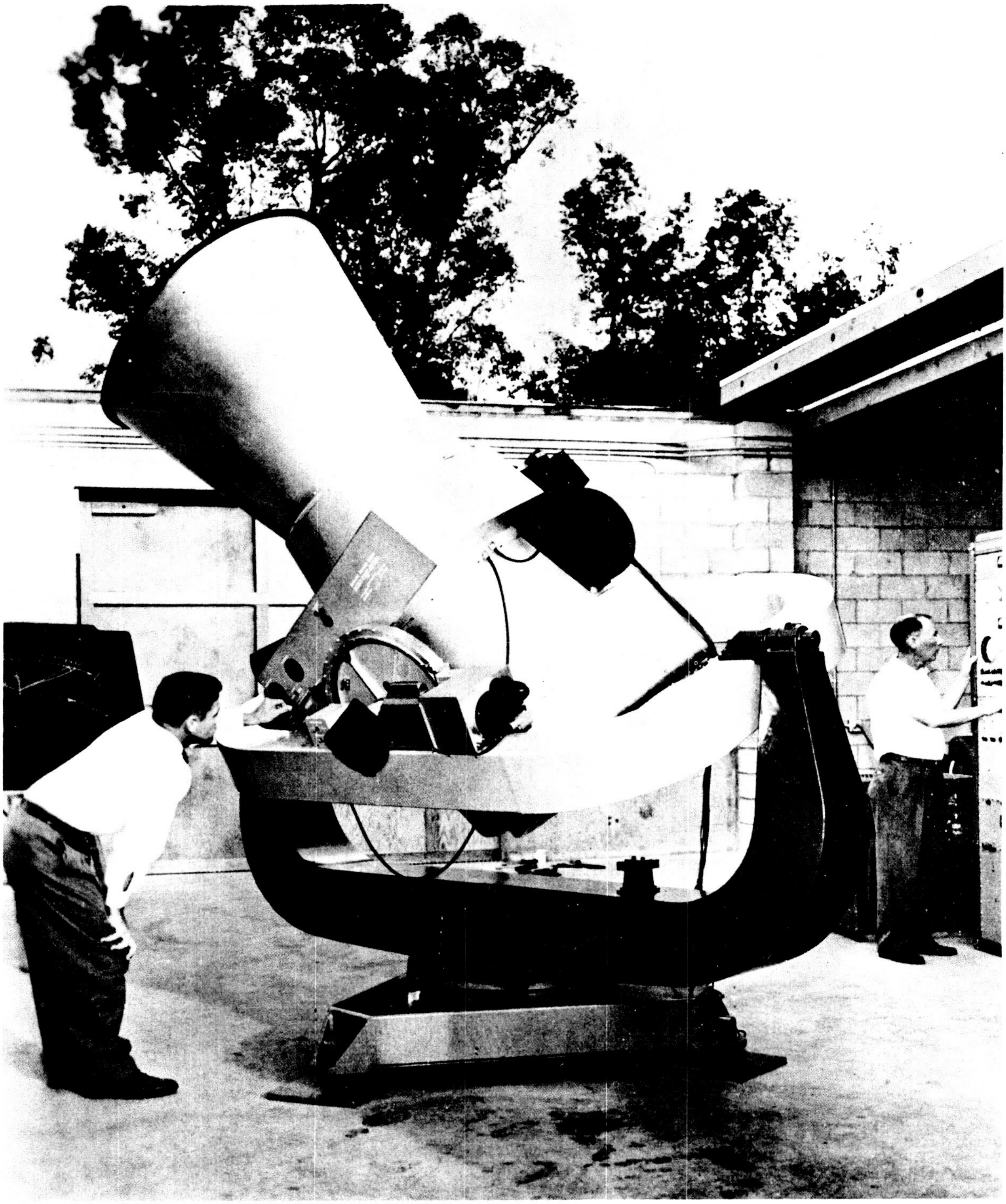

Figure 8.--The three axes of the Baker-Nunn camera and the horizontal leveling screws are clearly shown in the photograph.

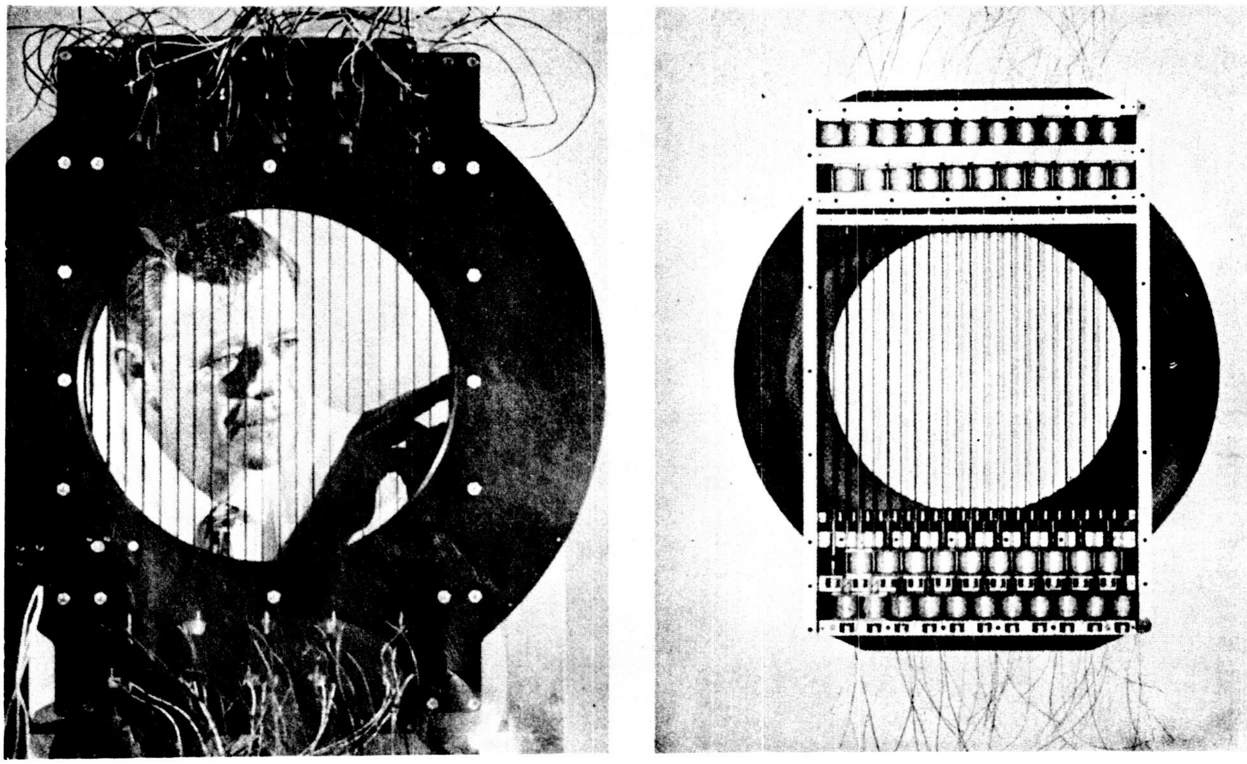

Figure 9.--This rotary solenoid-actuated louver shutter is located between the lens of a ballistic camera.

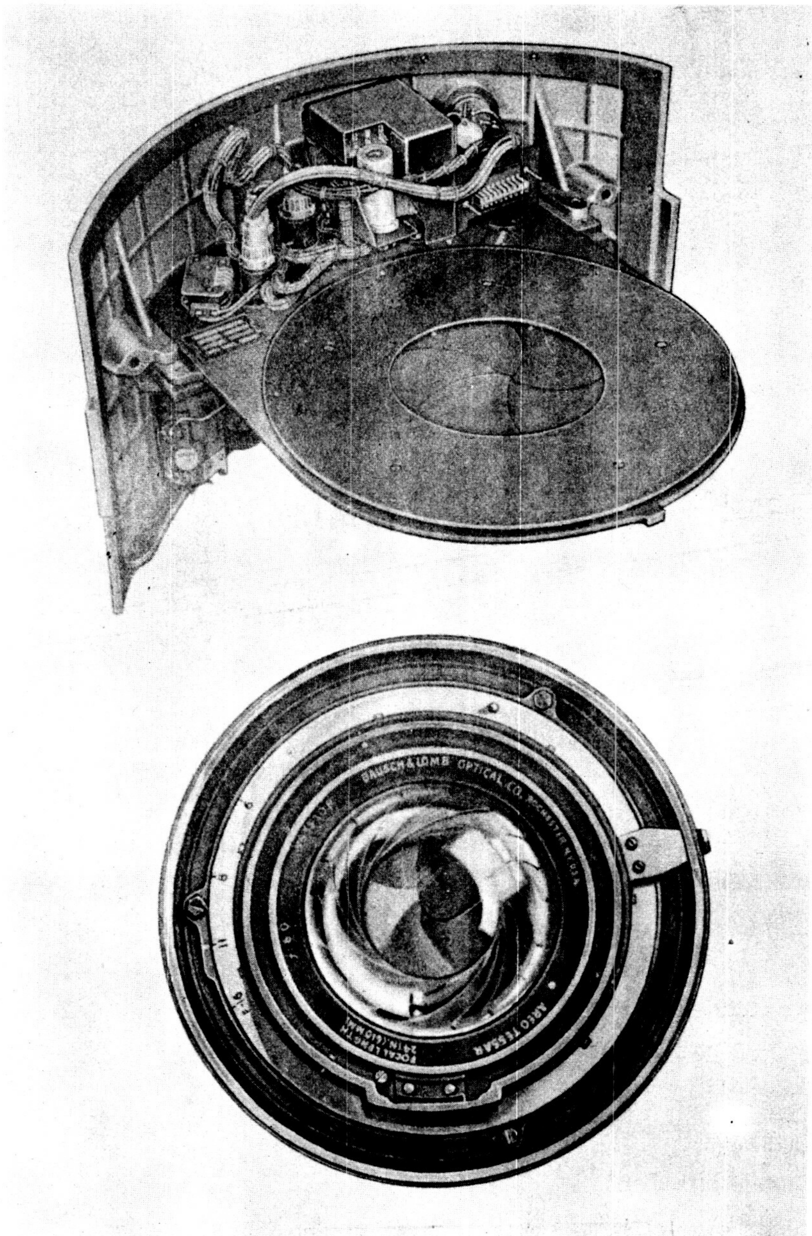

Figure 10.--The between-the-lens shutters of both the drawer (upper) and circular (lower) type are shown.

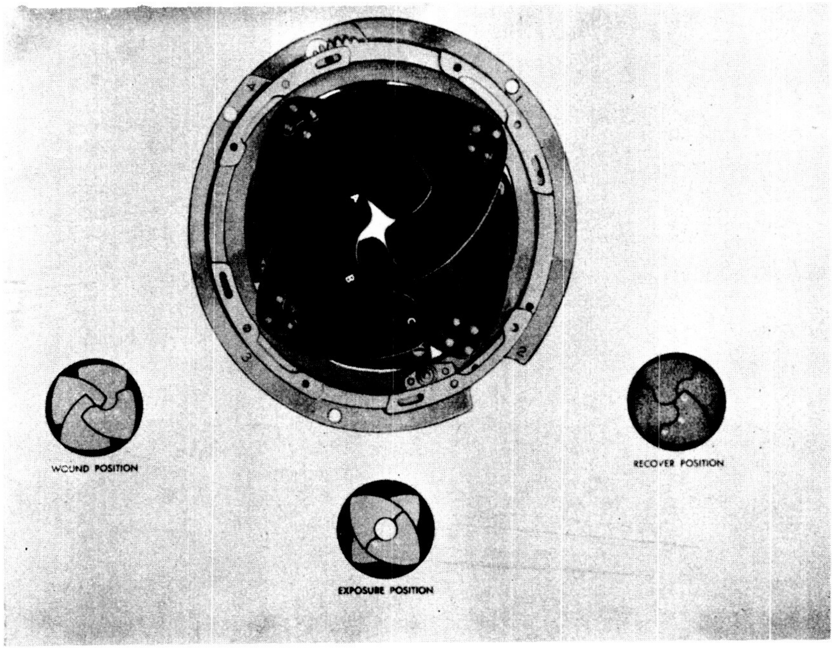

Figure 11.--Rapidyne intra-lens shutter.

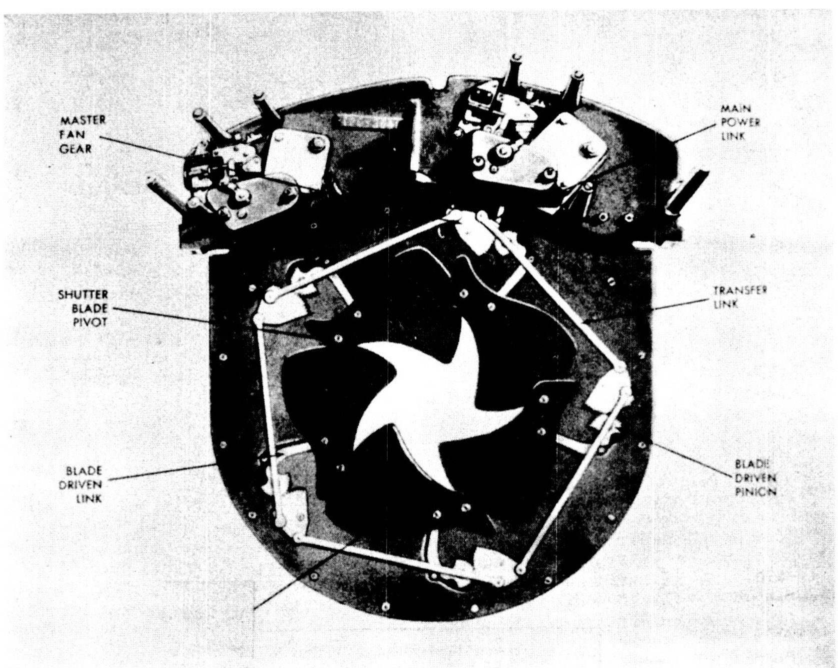

Figure 12.--The leaves of a high-speed uni-directional intra-lens shutter travel in one direction per exposure.

Another disadvantage of the large-aperture intra-lens shutter is the large size of necessary housing for the activating mechanism and linkage.

Focal-plane shutter

The focal-plane capping shutter is mounted near the focal plane and as close to the film or photographic plate as design considerations allow. This type of shutter has long been used in American aerial-photography cameras.

A focal-plane shutter in its simplest form consists of a light-proof curtain wider than the film and long enough to wind around the rollers located beyond the ends of the negative area.

Its advantages are simplicity of design, ease of location (i.e., the lens cone can be simplified, since special housing is not needed to hold the shutter between the lens cells), and high speed.

A Baker-Nunn camera uses a focal-plane capping shutter of a clamshell design (figure 13). Rather than one blade being activated to expose the film, two separate blades (each half of the clamshell) are activated by a cam, thereby exposing the strip of film. The blades close after each exposure, and another segment of film is passed into the camera.

Louver shutter

Louver shutters act like a variable neutral density filter, rather than like a varying aperture diaphragm, as do intra-lens. "They may be placed anywhere in the optical system that is convenient" (Cluff, 1952). However, the shutters should be located as close to the lens element as possible and certainly not near the focal plane. These can be built with short time constants.

The louvers are thin, narrow, rectangular blades linked to a drive mechanism, they operate as a unit similar to a Venetian blind on a window. A louver-shutter assembly is usually made up of a rectangular frame holding a number of blades supported at each end in ball bearings and attached by small gears or pinions to a rack. When the rack is activated, the blades are turned perpendicular to a plane parallel to the focal plane to allow light to reach the film or plate. When the louvers are in a deactivated position, an overlap is allowed to prevent light penetration.

The disadvantages of this type of shutter are that the louvers, when in a vertical position, tend to block a small amount of light entering, owing to their thickness; and that the blades block oblique rays from reaching the film, owing to their width, thereby decreasing the efficiency of the camera system. They cannot be used near real imaging points of the lens system.

The advantages in using a louver system, however, are that a greater operational speed is possible and that there is a decrease in the size of the total unit.

Objective capping shutter

The before-the-lens or objective capping shutter is extremely simple, efficient and inexpensive. A gross shutter that merely opens and closes to determine the length of exposure, is usually used in conjunction with a coding shutter or chopper. The capping shutter shown in figure 14 is operated by a rotary solenoid activated by an 18-volt DC pulse.

Choppers

When either the satellite or the stars are trailing, breaks must be provided as reference points for position measurement and time determination.

The breaks are made by a chopping shutter used in conjunction with the capping shutter. It is possible, however, for the capping shutter to provide the chop; this method is used in certain ballistic cameras with louvered shutters.

Cameras with shutters having a high actuation and recovery speed are usually used in the latter case. Solenoid-operated louvered shutters fall into this class; able to open or close in 2 milliseconds, they can be programmed to remain open for any length of time.

A Baker-Nunn camera uses a rotating barrel-chopper with all but two "staves" missing. The "clamshell" shutter acts as the capping mechanism. The chopper briefly interrupts the exposure (as determined by a gross clamshell shutter) five times, chopping the trail into six segments separated by short breaks. The length of each break corresponds to the time interval during which the chopper covered the star field. The break-length in seconds is 1/20 of the whole exposure time, and 1/5 of the interval between two neighboring breaks (figure 15). At the instant of the third (the central) break, the time of exposure is photographed on the film.

When both satellite and stars are trailed, the center of the central break of the satellite image is measured with respect to the center of the central break of stars with known celestial coordinates. If the camera is tracking the satellite, the point image of the satellite is measured against the central breaks of the reference stars (Lassovszky, 1960).

If a chopper is used to interrupt the trail of the satellite or the stars, a correction must be applied either to the position or to the time to allow for the fact that the shutter has a finite speed (Veis, 1960; and figure 16).

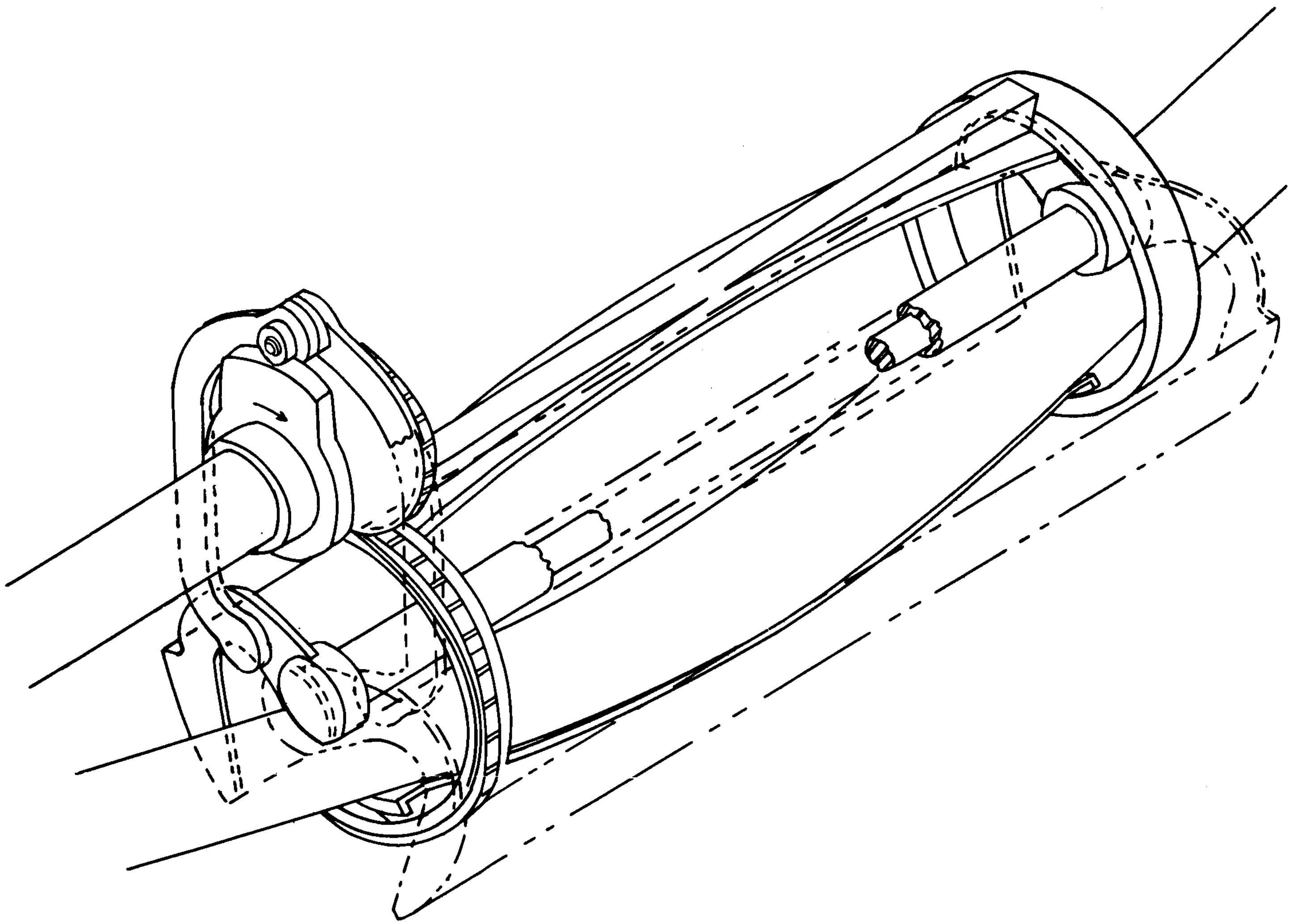

Figure 13.--Clam-shell shutter of Baker-Nunn camera.

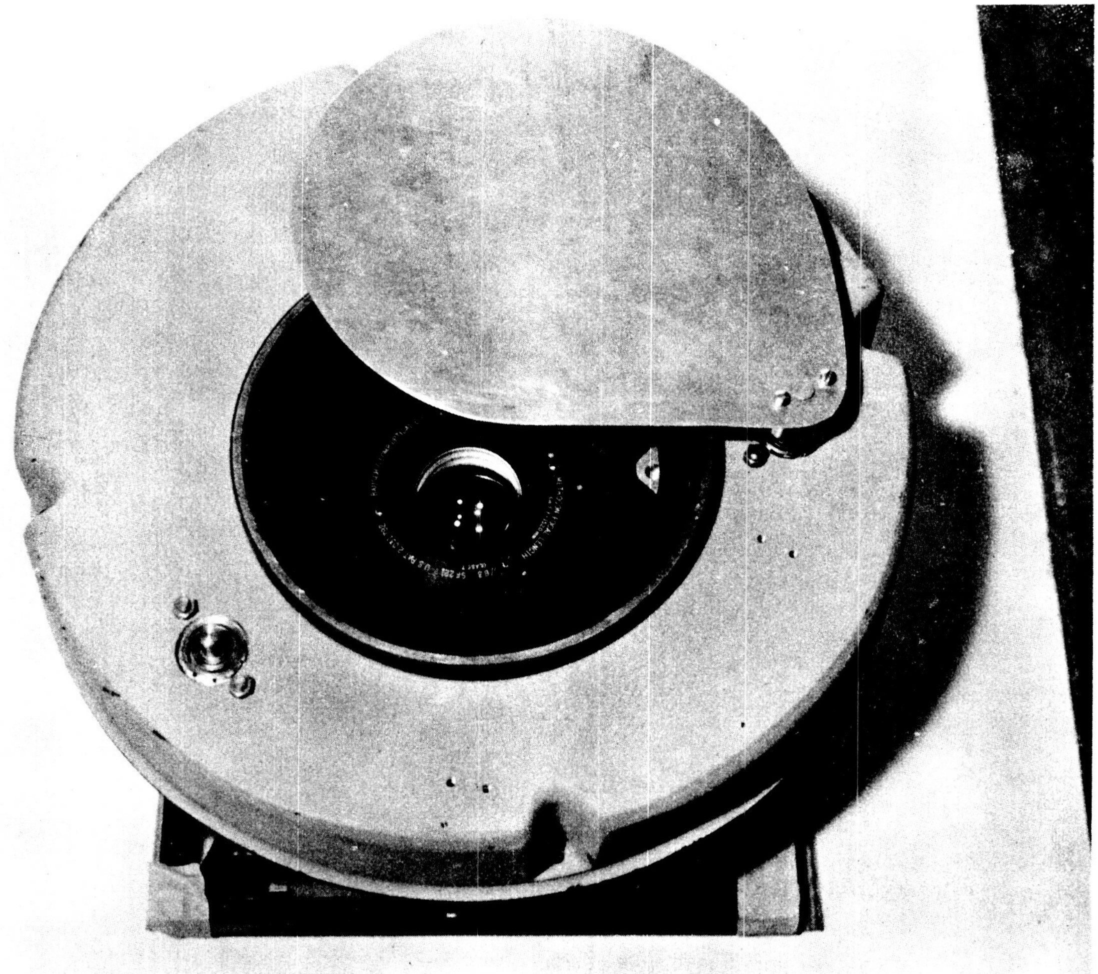

Figure 14.--Simplified capping shutter (note use of rotary solenoid).

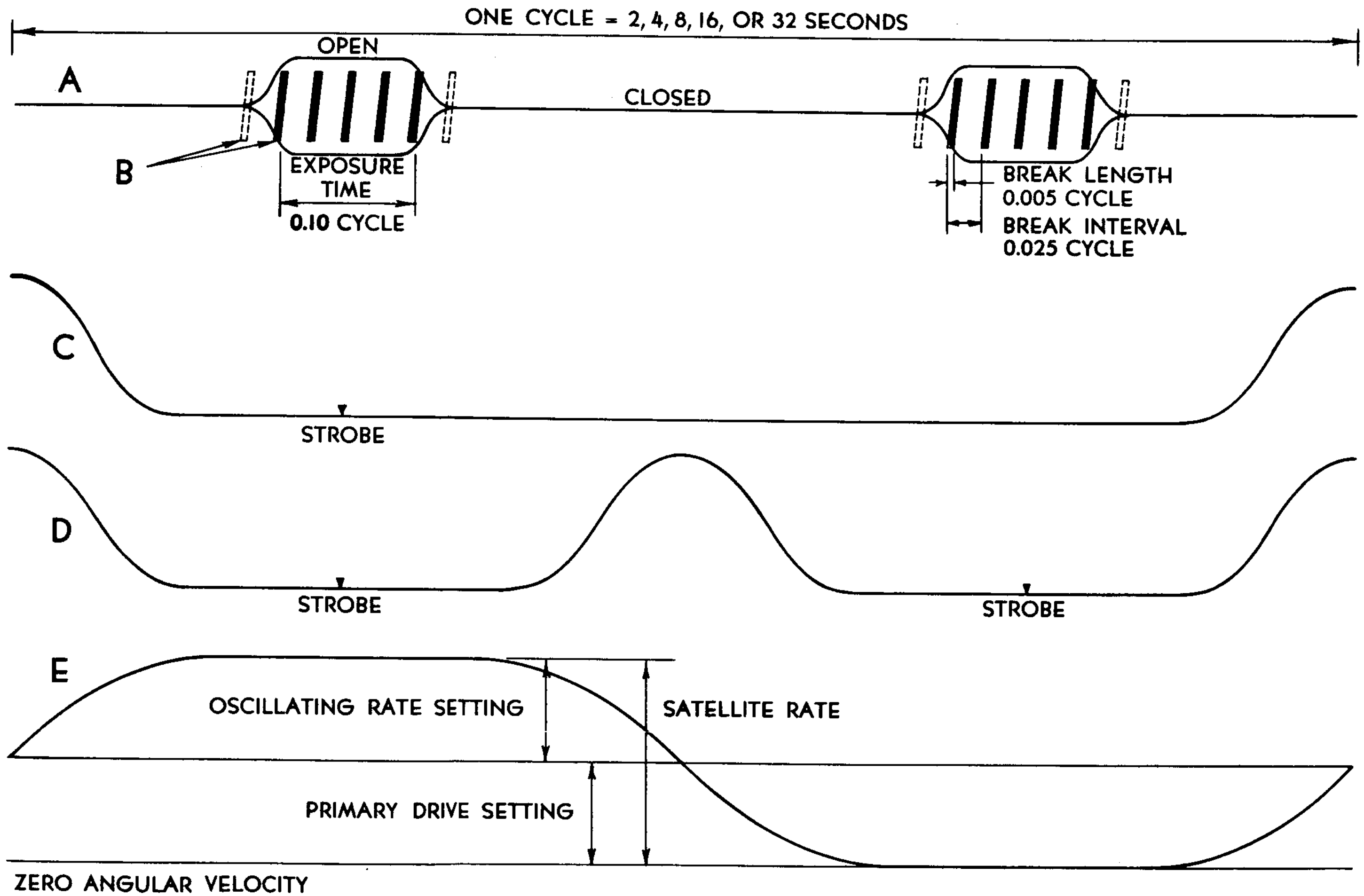

Figure 15.--A complete cycle of the Baker-Nunn camera shutter operation is shown.

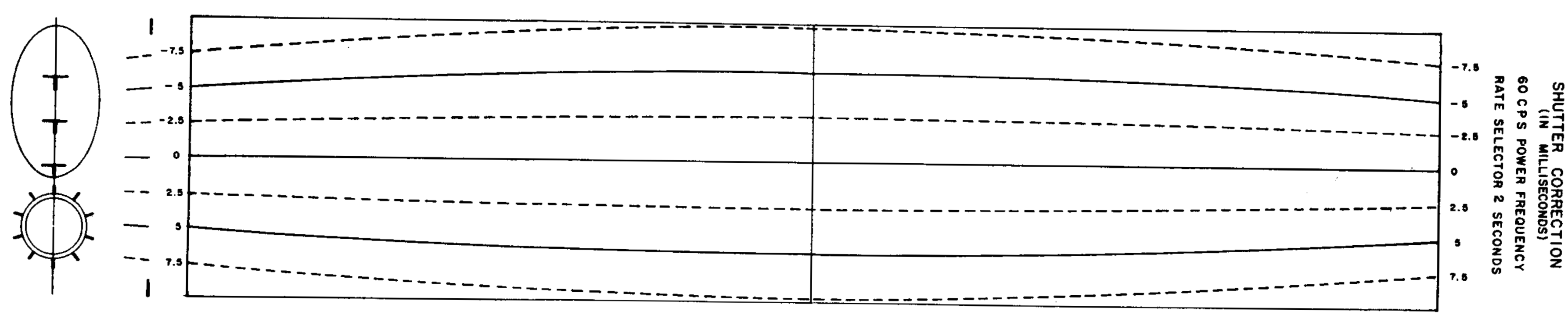

Figure 16.--Shutter correction (in milliseconds) of Baker-Nunn camera.

Shutter activation devices

When used for satellite photography the various types of shutter devices described above, except that of the Baker-Nunn, lend themselves to activation by pulse circuitry. That is, the activating mechanisms can be operated in response to pulses from a timing circuit. Timing circuits can readily be built to allow the length of exposure to be selected for one- or multiple-cycle exposures, as in the geodetic camera of the Smithsonian Astrophysical Observatory and the BC-4 camera (LaFond, 1961). The use of pulse circuitry and rotary or linear solenoids provides a readily controllable and sufficiently flexible shutter-activation system.

A continuously rotating motor-driven shutter provides pulses from its own synchronous operation. These pulses can be used to synchronize time display on the film at the proper moment.

Plates and films

Astronomical photography has long made use of the dimensional stability of glass. "Glass is yet to be surpassed as a base for photographic emulsions in critical applications where dimensional stability is paramount", (Eastman Kodak Co., 1961a). With a humidity coefficient of zero and a thermal expansion of .00001 cm per cm per degree centigrade, glass can be used with minimum precautions to ensure that it holds its size and flatness. "During processing the wet emulsion layer swells vertically but other dimensional changes are restrained. During the drying process the lateral dimensions of the layer remain essentially unchanged, but the vertical dimension may vary according to the treatment. Thereafter, the layer does not change dimension independently of its glass base", (Eastman Kodak Co., 1961b).

Research and development in the field of aerial photography have increased the physical strength and dimensional stability of film. Polyester film base made from polyethelene-terephthalate is being introduced for special aerial and satellite photography. Nevertheless, the use of film requires the design engineer to pay strict attention to the effects of humidity, tensile load, plastic flow, temperature, vacuum support, etc. It has been found, however, that with the proper design, photographic film can be used with negligible adverse effects.

For example, the Baker-Nunn camera uses 55.625 mm film stretched across an aspheric back-up plate (figure 17). When humidity, temperature, and creep are taken into account and when the film has been properly tensioned against the back-up plate, the accuracy of positive measurements is not influenced by distortion of the emulsion within an area of 5-cm diameter (Lassovszky, 1961). This corresponds to a field of 5.8°. Within this region use of the linear plate-constant method for reducing the measurements is justified. The error in the measurement of film from the Baker-Nunn camera is on the order of 2.3 μ when a linear fit is used (Lassovszky, 1961), while that of standard Eastman Kodak 103a-F plates is 1.6 μ when a linear fit of the data is used (Altman and Ball, 1961).

When the focal plane is curved, or when the cameras will be taking a number of exposures of a satellite on a single pass or photographing many passes in one night's operation, photographic film should definitely be used. The added complexity of a film transporting system is more than offset by the convenient operation that is possible. For those cameras that have a flat focal plane (such as is found in many aerial cameras that can be modified for satellite photography work) and that do not track or do so only at sidereal rate, photographic plates should be used in order to avoid the complication of film-support systems.

Several types of photographic films and plates used for satellite photography are not factory-stocked and thus are available only on special order. In certain cases, even the special order requires the purchase of a large minimum amount of photographic material. It possible, standard film should be used, especially by stations producing only a few exposures; in this way, purchase and storage costs are kept low.

Photographic plates and films should be shipped and stored at the temperatures recommended by the manufacturer. This is especially true of spectroscopic films and plates and of very fast films. After the photographic plates and films have been removed from a refrigerator or deep freeze, at least four hours should be allowed for the materials to reach approximate room temperature. This procedure will prevent condensation of moisture on the cold surfaces (Eastman Kodak Co., 1962).

Processing should be carefully controlled to produce the desired results. The satellite and star images should be as small as possible consistent with the requirements for positive identification. Contrast should be as high as possible consistent with the use of highly sensitive emulsions. In the final selection of film for use with any optical system, it is necessary to test the best available emulsions in the field. Variations in manufacture can cause variations from published specifications large enough to make it advisable to check each batch of emulsion under operating conditions. These variations may even be large enough to prompt selection of seemingly poorer film that gives better over-all results in actual use.

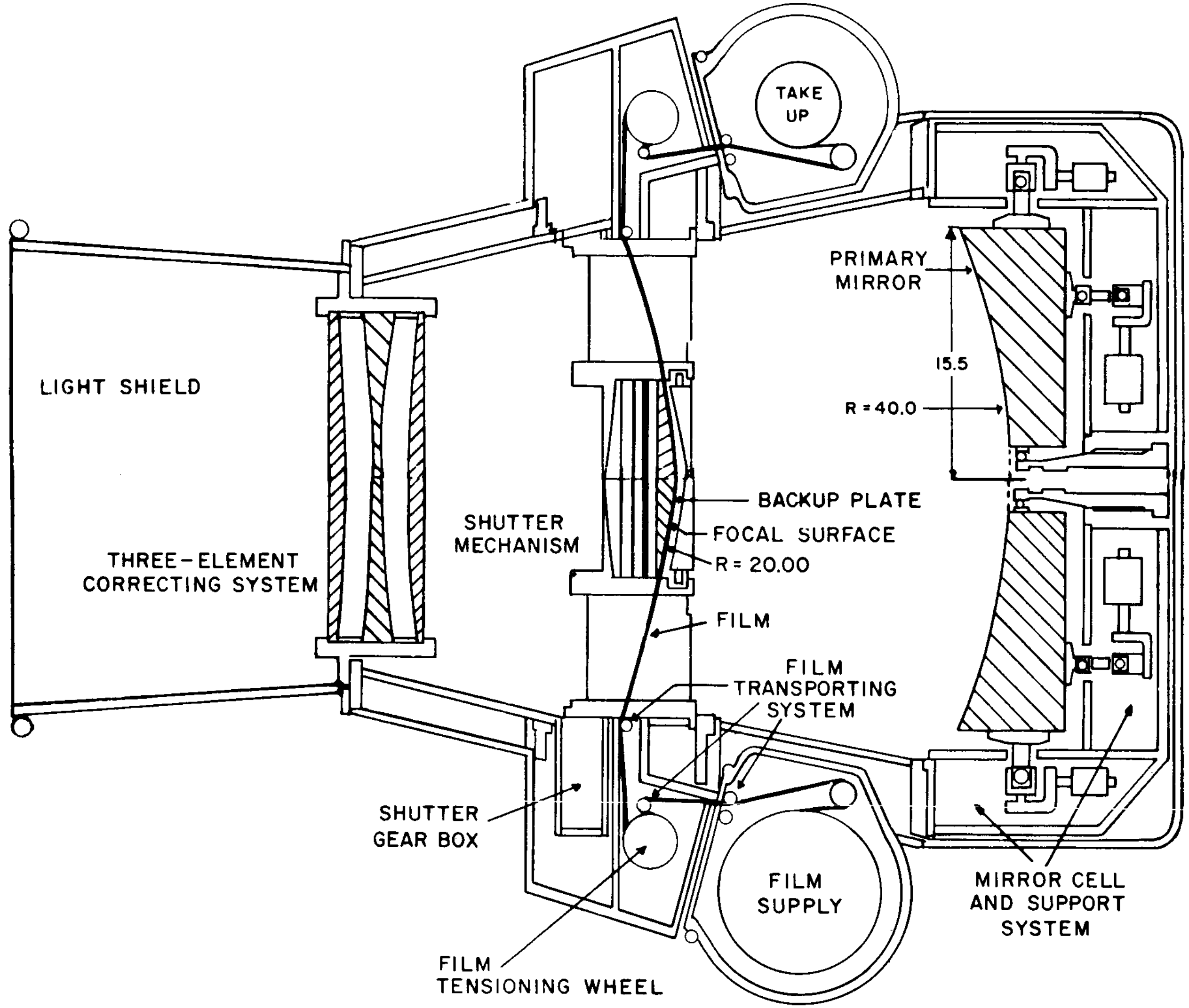

Figure 17.--The cross-section of the Baker-Nunn camera shows the curved back-up plate and film transport system.

Timing

General requirements

Timing of an observation must be sufficiently accurate to determine the finally located position of the observing station to about 10 meters. This is equivalent to determining the position of a satellite orbiting some 1000 km above the earth's surface, to a precision of 10 meters, or to about 0.001 second of time.

Precision of shutters

Since we have postulated various camera systems having similar focal lengths but different purposes, the basic differences in timing depend on the projected use of the equipment.

For flashing-light objects, the effective exposure is not increased by tracking, so the camera can be left stationary and still provide good point images for the flashes. Since the flash time is defined by a clock in the satellite, shutter timing is needed only to determine the positions of the stars. For the maximum sidereal motion of 15 seconds of arc per second of time, defining the end of a star trail to 1 second of arc requires 1/15 second of time shutter accuracy. The minimal shutter accuracy needed is 1/20 second, yielding measured positions to 1.04 second of arc precision at the center of a star trail. This we will take as the shutter requirement for the camera recording only flashing-light objects.

For a camera tracking sidereally, less accuracy is needed. The shutter must be opened before the first and closed after the last flash. Inaccuracies of more than a few seconds require longer exposure times to ensure recording the flashes. This increases the background fog, possibly enough to mask the flash images.

Note also that large uncertainties in timing the beginnings and the ends of exposures (with consequent long exposure times) require a much more accurate polar-axis adjustment and sidereal guiding system than do small uncertainties. Errors in the timing and in stellar guiding introduce errors into satellite positions relative to the stars. Therefore, if good results are expected, the times should be known to within a second or two. For this accuracy a chronometer, or short-wave radio reception of a standard time signal should be sufficient.

If the camera is provided with a calibrated chopping shutter, positions of sunlit satellites can be determined. This determination is limited by the accuracy of the local clock, by the accuracy of the timing pulse, by the calibration of the timing shutter, by the determination of the propagation time of the radio signal, by determination of radio and clock time delay, and by the accuracy to which the radio time service can be compared to a uniform time system.

A camera required to photograph all satellites must accurately track the faint objects to lengthen effective exposure time. This causes the stars to trail at a rapid rate, possible several thousands of seconds of arc per second of time. For satellite positional accuracy of 1 second of 1 second of arc, the star motion must be effectively stopped at some instant known to a time accuracy equivalent to the required positional accuracy, i. e., about 1 millisecond. For geodetic satellites, angular velocities range from three hundred to about 1000 seconds of arc per second. The required timing accuracy for position reductions of 1 second of arc is therefore between 0.001 to 0.0035 second, or 0.001 second if the equipment is to be fully usable.

In summary:

Type A: The shutter must be as accurate as possible, minimum accuracy being 0.001 second for geodetic satellites. There should also be some means of ensuring that the chopping camera shutter is open at the time of the light flashes.

Type B1: For flashing-light objects, the position of the stars on the plate is independent of time, and the time of the flash is known. Hence only crude timing is necessary, to an accuracy of about 1 second. (However, some means, either a star chart or a second plate, must be used to identify the flashes.)

When this type of camera is used to observe bright passive satellites, the end of the satellite image must be related to time, even though the stars need not be. Therefore, a high-accuracy shutter, equivalent to that of type A, is necessary. Without the type A shutter, the camera is equivalent to type C1.

Type B2: To determine the satellite position relative to the stars, at the time of flash, one must measure the position relative to each end of the trail and interpolate to the proper time. Timing accuracy of the trail ends must be sufficient to yield positional accuracy better than 1 second of arc, or 0.05 second of time.

When this camera is to photograph passive satellites, it must have a shutter to give accurate timing to some points (normally each end) on the satellite trail. For the proper precision, a type A shutter must be used; otherwise this camera will be equivalent to type C2.

Type C2: This camera to be used only for flashing satellites, will need only to define the ends of the star trails to about 1 second of arc. The shutter accuracy therefore required is only 0.05 second of time.

Type C1: This camera is to be used only for flashing satellites, and star positions are relatively independent of time. The satellite clock defines flash times, so only crude timing of shutter is necessary, to an accuracy of about 1 second of time.

Control of shutter timing

The means of assuring the time accuracy of the two types of shutters will, in general, be different. The shutter for a Class A station is necessarily regulated by a very precise frequency, and the time should be recorded against an accurately controlled standard clock. Mechanical equipment, such as a drum chronograph, has been found to be insufficient for this purpose. The most efficient way to record time is probably on the same film as the satellite is photographed, by recording a clock illuminated electronically by a flashtube at the time of interest. The clock should be controlled by a precise quartz crystal, or its equivalent, the frequency of which is checked daily or more often against a radio time standard, such as WWV, GBR, NBA or ZUO. This check is used to relate shutter time to a uniform system such as A_1 or UT_2. All possible sources of error must be eliminated or calibrated, such as the position of the shutter at the instant that time is recorded, the connection between the crystal-controlled clock and the clock in the camera (if they are not the same), the internal time delays in such items as radio receivers, etc. Calibrations for all critical settings or equipment should be made for each exposure, automatically if possible. All data on all equipment used must be available (published) for reduction of the film or plate and for subsequent use of film data.

The lower accuracy of the Type C shutter allows a much simpler and less expensive recording method to be used. A radio receiver and a drum chronograph, tape recorder, or equivalent may be used. The second markers from the radio receiver (or a local chronometer) can be fed to the chronograph pen. At the same time, an impulse generated by the shutter opening and closing is fed to the same pen. The shutter marks may be interpolated, between timing markers to an accuracy of at least one part in twenty, yielding $0^s.05$ time precision. The tape recorder may be used in roughly the same fashion, as described by Allen (1961). A solution of iron carbonyl--$Fe(CO)_4$, $Fe(CO)_5$, or $Fe(CO)_9$--suspended in normal heptane can be used to "develop" the tape. In either case, calibration of drum or tape speed should be made periodically, especially where power frequency is known to vary.

For local time mark generators (chronometers), a check against some radio time standard must be made before and after the observation.

Other possibilities are available for timing, e.g., photographing a master clock with a separate camera and a strobe light fired at a known point in the exposure; or moving either the camera or the plate at right angles to the satellite trail in synchronism with a time signal (the time of the first jog being recorded to the nearest second). A daily or more frequent check of time calibration must still be made.

The camera timing system of the Baker-Nunn is designed to give a basic accuracy of 0.001 second. It consists of a crystal-controlled frequency standard and associated divider circuits, a radio for comparison of time with WWV or other time signal, a clock readout, a slave clock that is photographed on each transit record, and a shutter calibrator that indicates the exact position of the shutter at the time recorded on the film.

The oscillator clock and radio are available commercially; the slave clock and shutter calibrator were specially made for the Baker-Nunn camera.

Since the focal-plane shutter of the Baker-Nunn takes a finite time to cross the film, it is very important that the position of the shutter at the time of the photograph be known. Therefore, a shutter calibrator is very necessary in this system (Henize, 1957; Davis, 1958). The calibration consists of a second strobe flash, in a narrow collimated beam, produced so that it strikes the end of the chopping shutter blade, thus throwing a shadow on the film. The position of the shadow gives the exact position of the shutter for the time recorded on the film.

Operations

Predictions

Predictions for the various types of stations are merely variations of one set of data, i.e., topocentric position of the satellite at some specific time. These data are most easily calculated by a computing machine at some central location where either previous observations or orbital data are available. Once prepared, the topocentric position is easily transformed into circle settings for each camera. This information can then be transmitted to the observing station by the most convenient means (see Data center).

The predictions should be sufficient to allow pointing of the optical axis of the camera within ± 1 degree of the satellite at all times.

Field reduction

Field reduction of the photographs is generally necessary only for rapid production of medium-accuracy observations to be used to prepare predictions. Rapid communications, such as telegraph, must therefore always be used when a field reduction is needed. Not many medium-accuracy observations are required, because for prediction purposes an orbit can be maintained with 25 to 30 observations per week. These measurements may be made with a two-screw comparator; however, use of overlay film-scale charts or projection of the images onto standard charts has been found to be efficient and sufficient for pratical purposes.

Most stations will not need to supply a field reduction, and many cannot perform the precise reduction at the observing site. In these cases, the observing staff need only:

1. Observe by following the predictions, and make the necessary logs of procedures;

2. Process the film;

3. Scan the film, locate the images, and mark them;

4. Ship all necessary information to the measuring center.

If the observing station performs the precise reduction, the minimum requirements are:

1. A two-screw measuring engine capable of a resolution of the equivalent of 2 seconds of arc or better.

2. A set of star charts for identifying the satellite. This may be replaced by a second plate of the region taken at a slightly different time.

3. A set of catalogues with stellar positions at least as accurate as those of the AGK2 or Yale Zones, for reduction of the satellite positions.

4. A table computing machine and trigonometric tables.

A standard method of plate reduction can easily be modified to give a reduction procedure for all films (see Smart, 1956).

Quality control

The quality of the data output from all the cameras should be controled in several steps. The quality of the predictions is controlled by the observing sites reporting errors and non-observation when conditions are otherwise good. Quality of observing procedures is ensured by double-checking camera settings and other standard practices. Equipment condition should be monitored by periodically checking the shutter timing, clock operation, mount orientation, and similar details. If necessary, calibration of essential items, such as the shutter, should be built into the camera, even though this entails some extra expense. Examples of these procedures would be as follows:

1. A tube designed to flash at exposure center, in Class B or A cameras, to give photographically the position of a focal-plane shutter when exposure time is recorded.

2. Daily monitoring of the local time system against a radio time standard, to derive absolute difference and rate. Systems using mechanical clockwork, such as chronographs, may be self-calibrating, but the observer should periodically check whether the motion of the drum is uniform.

3. A weekly or monthly check of camera focus and mount orientation. The setting circles should be checked to ascertain that they properly point the camera. The camera should be focussed to ensure that image quality, magnitude reach, and therefore high quality of measured position are maintained.

Control of film processing can be maintained by following a predetermined method of processing and by checking the procedure periodically by processing exposed film of known characteristics; for example, a sensitometer wedge or a standard star sequence can be used for comparison.

Control of the quality of the final data should be ensured by periodic tests of the measuring procedures and computing techniques. The most important point, however, is to ensure that all field operations that may affect the final results are known and allowed for in the final reduction of time and position data. Data of the accuracy necessary for intercontinental geodetic connections must meet the standard usually found only in the laboratory; to achieve this standard under field conditions requires much more effort in controlling and checking than in actually obtaining the data.

Communications

The type of communications used at a station depends upon the work load. If the station is used only for the tracking of geodetic satellites, communication by mail will probably be satisfactory.

However, for the more advanced stations with higher work loads more complex communication systems will be needed.

A Class A station will need, at a minimum, a teletype machine connected by land line to the nearest telegraph office. The ideal situation station would be a radioteletype link to the nearest center which can make preditions available.

If more advanced communications systems are to be used, the initial plans for the physical plant should contain space reserved for communications.

Physical plant, logistics and personnel

Selection of sites

Whatever the class of station, it should stand on an elevated site sufficiently distant from any large population center to afford a dark night sky and a low, uncluttered horizon. There should be minimum wind or wind-borne dust. A reliable water supply and a dependable electrical power featuring fairly constant voltage and frequency with few failures are essential, although the power requirements can possibly be relaxed for a Class C station.

As soon as a site is selected, it should be surveyed into the best geodetic system available.

Buildings

A large Class A camera is quite powerful and complicated, and will generally be used for a full research program. Consequently, it will require a larger, more flexible station than will a Class B or Class C camera.

Figure 18 shows a plan for a Baker-Nunn station engaged in a full-time observing program. The obvious advantage of a station consolidated in one building on one level is the closer location of all working areas to the camera. The main disadvantage is the close proximity of the sun-heated roof to the camera, and the attendant possibility of disturbances in seeing.

Another, but more costly, solution is the two-story construction in which the camera is on the second story, and the offices and laboratories ring the base of the camera on the lower floor. This design is closer to standard observatory practice and will provide better seeing since the camera will be above ground mist.

Because of the high tracking rates and the necessarily fast motion of the cover of the telescope, a dome is an impractical way to cover a satellite tracking camera.

A rolling roof, powered for the convenience of the observer, provides a much more satisfactory solution. The station may have a single roof rolling in one direction, or a split roof with the halves travelling in opposite directions. The split roof requires longer total rail length, and if split in the center, there is a possibility of leakage over the camera. However, one half of the roof is often used to protect the camera from the wind. A single roof usually presents problems with the sealing end flap. However, leakage at this point is not so important as leakage over the camera.

Station plans can be simpler for smaller stations, 40 square meters of floor area being probably satisfactory for a Class B station.

For Class C stations the camera cover can be of simple design, ranging from a lift-off box cover or a hinged cover to more complex structures, preferably involving a wind screen. A concrete pier support, however, should always be provided. It eventually constitutes a substantial support for a geodetic marker in the case of a temporary camera installation.

All stations must provide a well-designed space whether large or small, assigned specifically to the keeping of records. Thoroughness of recording keeping is critical to a successful station of any class.

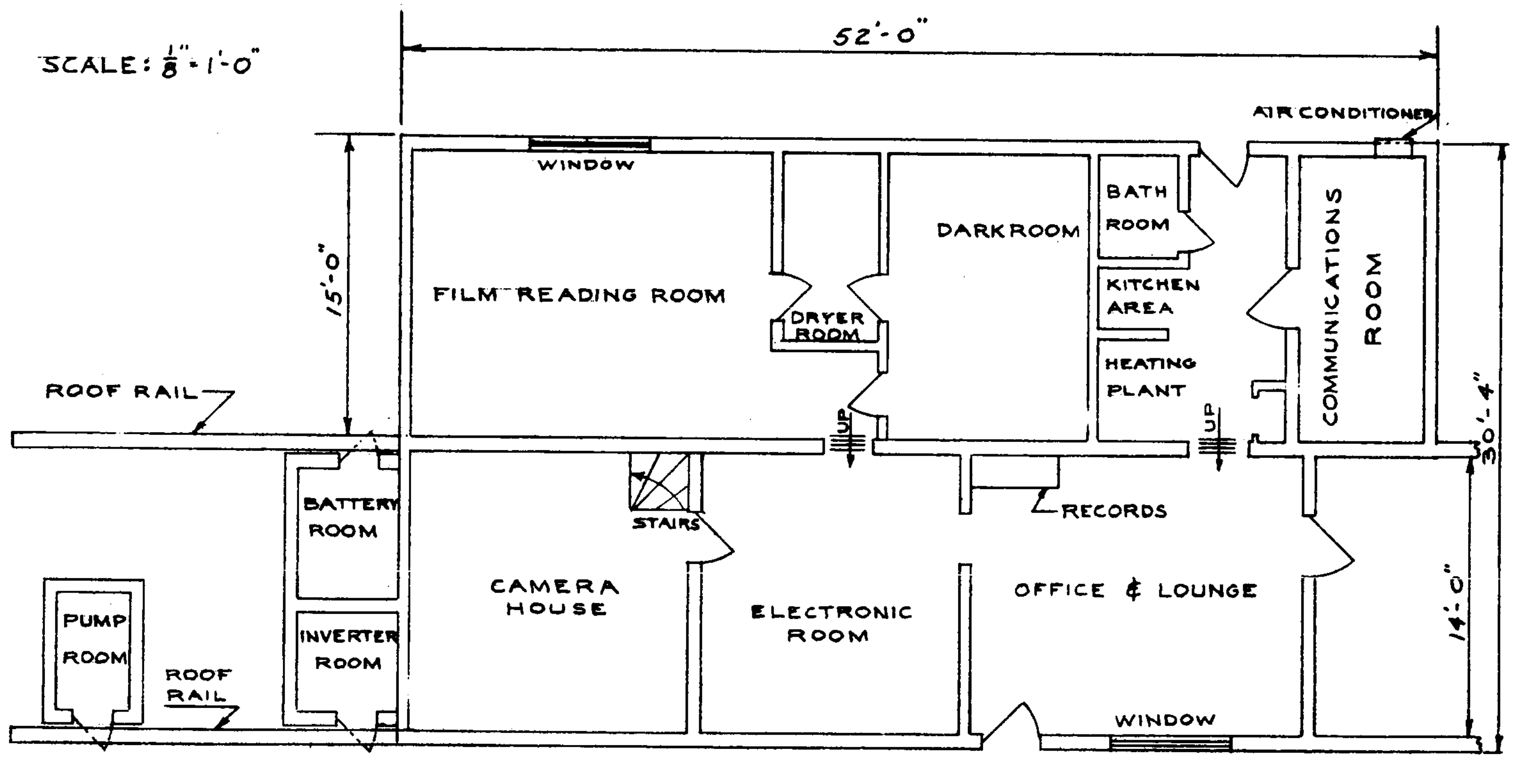

Figure 18.--Plan of Baker-Nunn station.

If a portable geodetic station is desired, the design can be based on two trailers. With a floor area less than 10^{0} square meters, a Class C station can still operate efficiently. Moving the equipment can be relatively easy. Even with a station as large and complex as the Baker-Nunn, it takes less than one day for a crew of six men with a crane to disassemble the equipment for shipping.

Emergency power supply

All Class A and probably Class B stations should be provided with emergency equipment for generating electric power. A common arrangement is a 5- or 10-KW gasoline-driven unit, or a 37.5-KW or larger diesel unit; 5-KW power represent a minimal operational capability; at least 10-KW power is required for adequate operation, and 37.5-KW allows full operation with no restrictions on the use of such items as air conditioners and electric heaters. If it is to be operated when power is lost, a Class A station should be provided with at least 30 KW of emergency power.

The emergency supply to provide uninterrupted power for a time standard consists of a battery bank, a battery charger, and a rotary converter that converts direct current from the battery bank to alternating current. The time standard for the system is operated continuously from the converter, and the batteries are continuously charged.

Transfer switches and vibrator inverters have not been found satisfactory.

Darkroom

Proper darkroom facilities are extremely important. An Eastman Kodak Co. manual (1961c) provides very good guidelines for darkroom design. Ultimately the design used for the darkroom depends primarily on two factors:

1. The workload which influences the degree of automation used;

2. The type of plate or film used.

Baker-Nunn station darkroom equipment consists of 5 or 6 Nikor tanks plus several Nikor reels for 100-foot lengths of film, and a loading stand (see figure 19); a sink large enough to hold all tanks; and space for a drying reel. Also there are timers, thermometers, and chemical mixing and measuring equipment.

Film is conveniently dried on a drying reel of 4-foot diameter rotating at several hundred revolutions per minute. Ideally this reel is located in a separate room or alcove equipped with heat lamps and kept relatively free from dust.

Some stations dry film directly on the reel by the method suggested by the Nikor company.

A Class C station that observes only flashing satellites and therefore has a very small workload can use hand development in small tanks or trays and air drying. This can be done in a darkroom on not much more than 1-1/2 meters square.

A darkroom for a Class B station might be as simple as that for a C station or as complex as that for an A station depending on workload.

Logistics

Logistics here involves the critical requirement to have people and things where needed when needed. It can be managed partly by formula and partly by experience as a station progresses. Whether a station is self-sufficient is a matter of policy rather than a matter of station type, since all classes of station can be self-sufficient in most areas.

After the building is completed, a Class A station should if possible procure locally its own hardware, plumbing and building supplies. For a network of stations, central procurement and distribution of bulk-use items are the key to orderliness in funds devoted to building and maintaining inventory. They also ensure uniformity of type and quality. Examples of items that should be procured centrally are: film, plates, photographic chemicals, film processing equipment, exposed-film shipping containers; film or plate reduction aids; satellite-passage record forms and other report forms.

As a satellite tracking network comes of age, unforeseen weaknesses of the station equipment become apparent as the result of repeated failure of certain components. At such time, redesign or increase in the inventory of these components is indicated. Monitoring of such problems is simplified if procurement is centralized.

An initial shipment of supplies, including consumables, should be sent to the station. The person in charge should then determine the quantity of centrally procured items that is necessary, and request that amount from headquarters on an "as-needed" basis. His experience concerning storage space available and delays in delivery is better than arbitrary scheduling of shipments.

A Class C station might effectively be made almost completely self-sufficient especially if its photographic system is designed to use standard film. However, since the rate at which most items are used at a Class C station is low, savings might be made by bulk purchases at a headquarters.

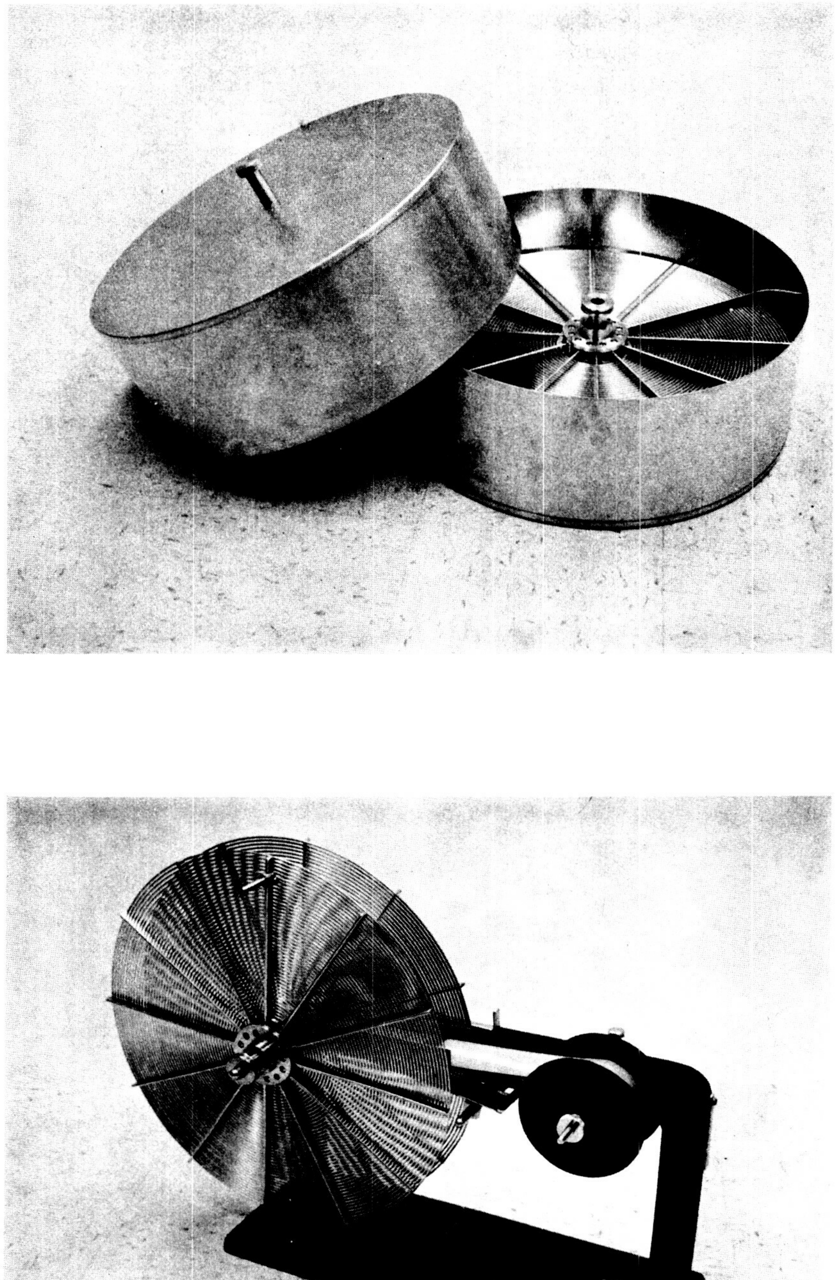

Figure 19.--Nikor processing equipment.

Personnel

A Class A station operating seven days a week will probably require a station director and six observers to track approximately 15 satellites per night. Unlighted satellites depend on reflected sunlight from outside the cone of the earth's shadow to make the image on the camera film or plate. Since the photography must be done from sometime after dusk until nearly midnight, and again from sometime after midnight until nearly dawn, observing is a full-time occupation. A sophisticated camera of the type used at a Class A station can usually be operated by one man, but two men per shift, whether all night shifts or split shifts, ensure more certain acquisition of photographs--weather, camera and timing all assumed to be operational.

The choice of staff to man a Class A station is less restrictive than for smaller stations, because the necessary observing techniques can be taught, and knowledge of electronics, mechanics, optics or astronomy can be a specialty of one individual observer. A station director should be conversant with all aspects of station operation and must be an expert observer. He must regularly observe with each crew member so that he can teach new techniques provided from headquarters and assess the value of each of his men.

Staffing of Class B stations requires more care. Four men are probably sufficient for the work load. The same general specialties, however, are important, although probably a lesser degree of proficiency in each specialty can be tolerated. Either observing for complete nights two or three times a week, or less than a full night by a single observer seven times a week is to be expected. To keep equipment in proper running order (maintenance and repair) requires time outside normal observing hours, otherwise, obervations will be lost.

Class C stations may be staffed with one or two professionals or with varying numbers of enthusiastic, dedicated amateurs who devote time as their regular jobs and family commitments permit. Non-professional staff may be recruited from amateur astronomical groups and their friends; perhaps some will be college students majoring in engineering or astronomy. Results, however, will depend critically upon the quality of the staff of these stations, more possibly than upon the quality of the equipment with which the observers work.

A highly mobile station, be it Class A, B or C, presents more supply problems than one that will be at one location for an extended period of time. Consequently, the more mobile a station the more carefully planned and self-sufficient it should be.

The data center

To be able to photograph satellites efficiently, all observing stations must be supplied with up-to-date ephemerides. While each observing site might compute its own predictions from the orbit of the satellite or from predictions of subsatellite points, it is much more convenient and efficient if predicted times and camera settings are prepared by some central group using a large digital computer. The same organization that computes satellite orbits should have the capability of preparing predictions.

Required for the best operation of such a data center are:

1. Access to a modern, high-speed electronic digital computer;

2. A programming staff that can provide computing routines to satisfy all requirements of the tracking stations, e.g., orbit computation for satellites of interest, predicted camera settings, data reduction, etc.;

3. Rapid access to sizable amounts of data of medium accuracy, ± 1 minute of arc or better, to be used to compute orbits;

4. A means of inexpensive communication of data to the observing sites in order to supply timely predictions;

5. A clearing house and publication facility for the final data from plates of all cameras, regardless of where and when they may be measured;

6. A complete list of the best available coordinates of participating stations, for preparation of predictions and reduction of final data.

The general operation of such a center can be on two basic levels: one for generating predictions, the other for preparing final data to determine the geodetic location of each station.

Predictions

From medium-accuracy observations of a satellite in a geodetically useful orbit (i.e., minimum altitude the order of 1000 km) predictions can be prepared for a useful interval of one to three weeks, depending on the amount of observational material and on other factors such as air-drag cross section or light-flash mechanism. The camera settings would be good to within 1 to 2 degrees for any time in this period. For wide-field cameras, predictions of slightly reduced accuracy might be useful for as long as four weeks.

Medium-accuracy observations from ten to twenty Class A observing stations suitably spread out in latitude and longitude would be sufficient to yield good orbital information for generating predictions. The minimum amount of data necessary for the Baker-Nunn network is on the order of 25 to 30 field-reduced observations per satellite per week. These data, which would probably not be used for any other work, should reach the data center no less often than once each week, to permit continuous improvement of the orbit. To ensure efficiency and to minimize communication difficulties, we assume the center and the stations should transmit these preliminary data by radio, telegraph or cable.

These data would be used to derive the new orbits and new predictions for camera settings. This information would be computed and distributed to all stations within a short time, a reasonable time limit being three days before transmission, to allow for efficient preparation for distribution. Normal air-mail distribution of the predictions to most places in the world would average no longer than 10 days, allowing approximately one week of useful predictions to be prepared each week. For unusual events, other means of distribution might be used; for example, a regional center, with rapid communication to the main center, could distribute predictions by suitable means within its area.

Some sample types of predictions are:

1. Altitude and azimuth or right ascension (or local hour angle) and declination of flashing satellites, for Class C or Class B cameras;

2. Right ascension or local hour angle, declination and brightness or angular velocity at some time, for Class B cameras;

3. Altitude, azimuth, tracking-circle setting, and rate of angular motion, or L.H.A., declination, direction of motion and angular velocity, for Class A cameras.

These formats are derived (in principle) from the same data, i.e., topocentric positions of the satellite at certain times; all can easily be prepared by one computing method using minor variations. This possibility makes it especially useful to allow one center to compute for all stations.

Precise plate measurements

Once predictions are furnished to all stations, the second level of operation commences. After a satellite has been photographed, the film developed, and an image found, the plate must be measured to the required accuracy of 1 to 3 seconds of arc. If the observing station or institution has the capability, the plates can be measured and the apparent time and position reduced by those most familiar with the camera and the timing equipment. If the necessary measuring engines are not available, the films should be measured at some central location. Convenience may suggest that this measurement center be physically located at the data center. In any case, the measuring center should have a complete description of the camera system and its operating characteristics, and a complete log of operation for each film, so that all necessary corrections can be applied to the final reduced positions. The same requirements apply to the clocks for sites needing accurate timing data.

The precisely reduced data should be transmitted to the data center by some preselected date, after which accurate orbits will be derived, all data will be checked, and the material will be made available to the geodetic investigators for their use in precise determination of the station location.

Publication of the observational data should be made by each station as they are obtained, but as the end result of the operation is to be a general set of geodetic connections made from all available data, the data center could be responsible for making suitable material available to all qualified investigators. Furthermore, considering the availability of computing and programming facilities at the data center, convenience may induce the investigators to do much of their work at the data center.

If the concept of the data center is carried to its logical end, consideration should also be given to the possibility of including other services, such as technical consulting facilities and a central purchasing and supply service for items difficult to procure in the vicinity of the local sites.

One example of the two-level system of data flow is the Satellite Tracking Program of the Smithsonian Astrophysical Observatory (see figure 20). When a satellite is launched, predictions based on the expected orbit are furnished to all observing stations. The first observations are reported by telegraph to the computing center. Accurate to between ± 1 degree and ± 1 minute of arc, they are used to correct the orbit and provide new predictions. The second preditions are usually accurate enough to allow Baker-Nunn cameras to photograph the object, yielding telegraphed observations of accuracies ± 1 to 3 minutes of arc. These are used to recompute the orbit weekly, providing new predictions one week in advance for the Baker-Nunn cameras. After preliminary measurement at the observing site, the film, camera log, and log of clock operation are forwarded to headquarters in Cambridge, where precision measurement and reduction are performed as required by scientific investigators. The data so produced are used to derive precise orbits, which are used by SAO staff scientists for research purposes.

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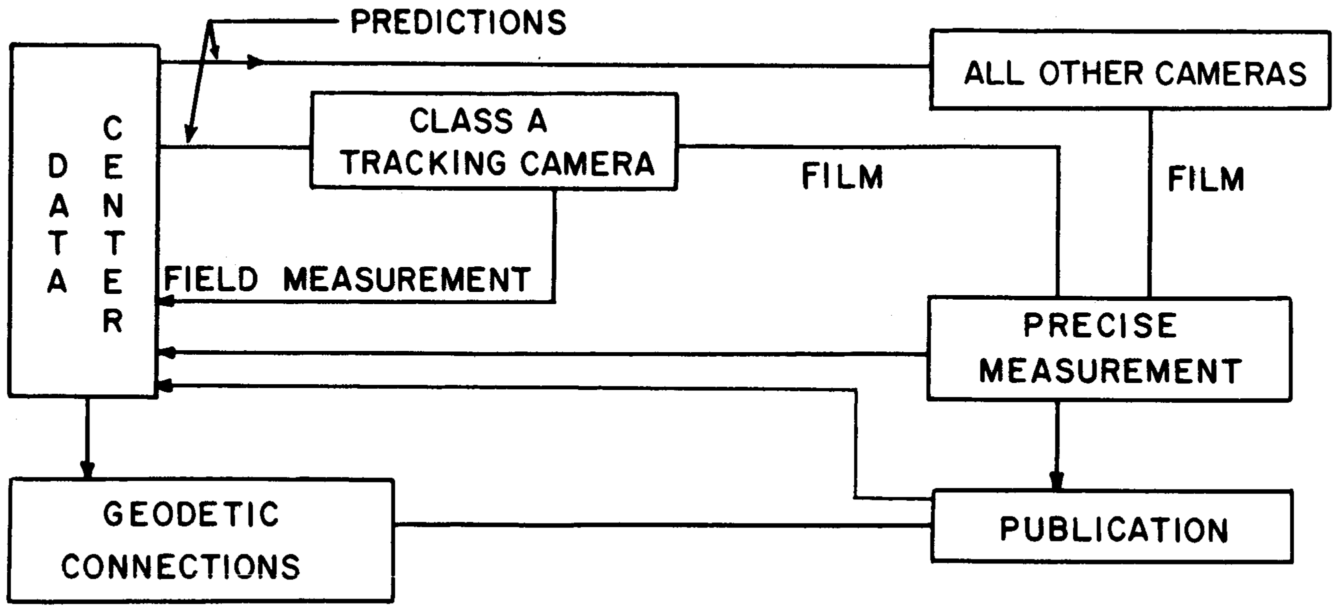

Figure 20.--Flow chart of data in satellite tracking program of Smithsonian Astrophysical Observatory.

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NOTICE

This series of Special Reports was instituted under the supervision of Dr. F. L. Whipple, Director of the Astrophysical Observatory of the Smithsonian Institution, shortly after the launching of the first artificial earth satellite on October 4, 1957. Contributions come from the Staff of the Observatory. First issued to ensure the immediate dissemination of data for satellite tracking, the Reports have continued to provide a rapid distribution of catalogues of satellite observations, orbital information, and preliminary results of data analyses prior to formal publication in the appropriate journals.

Edited and produced under the supervision of Mr. E. N. Hayes, the Reports are indexed by the Science and Technology Division of the Library of Congress, and are regularly distributed to all institutions participating in the U.S. space research program and to individual scientists who request them from the Administrative Officer, Technical Information, Smithsonian Astrophysical Observatory, Cambridge 38, Massachusetts.